Part I

2

Stream Corridor Processes, Characteristics, and Functions

Chapter 1 provided an overview of stream corridors and the many perspectives from which they should be viewed in terms of scale, equilibrium, and space. Each of these views can be seen as a "snapshot" of different aspects of a stream corridor.

Chapter 2 presents the stream corridor in motion, providing a basic understanding of the different processes that make the stream corridor look and function the way it does. While Chapter 1 presented still images, this chapter provides "film footage" to describe the processes, characteristics, and functions of stream corridors through time.

Section 2.A: Hydrologic and Hydraulic Processes

Understanding how water flows into and through stream corridors is critical to restorations. How fast, how much, how deep, how often, and when water flows are important basic questions that must be answered to make appropriate decisions about stream corridor restoration.

Figure 2.1: A stream corridor in motion.
Processes, characteristics, and functions shape stream corridors and make them look the way they do.

Section 2.B: Geomorphic Processes

This section combines basic hydrologic processes with physical or geomorphic functions and characteristics. Water flows through streams but is affected by the kinds of soils and alluvial features within the channel, in the floodplain, and in the uplands. The amount and kind of sediments carried by a stream *largely determines its equilibrium characteristics, including size, shape, and profile. Successful stream corridor restoration, whether active (requiring direct changes) or passive (management and removal of disturbance factors), depends on an understanding of how water and sediment are related to channel form and function and on what processes are involved with channel evolution.*

Section 2.C: Physical and Chemical Characteristics

The quality of water in the stream corridor is normally a primary objective of restoration, either to improve it to a desired condition, or to sustain it. Restoration should consider the physical and chemical characteristics that may not be readily apparent but that are nonetheless critical to the functions and processes of stream corridors. Changes in soil or water chemistry to achieve restoration goals usually involve managing or altering elements in the landscape or corridor.

Section 2.D: Biological Community Characteristics

The fish, wildlife, plants, and humans that use, live in, or just visit the stream corridor are key elements to consider in restoration. Typical goals are to restore, create, enhance or protect habitat to benefit life. It is important to understand how water flows, how sediment is transported, and how geomorphic features and processes evolve; however, a prerequisite to successful restoration is an understanding of the living parts of the system and how the physical and chemical processes affect the stream corridor.

Section 2.E: Functions and Dynamic Equilibrium

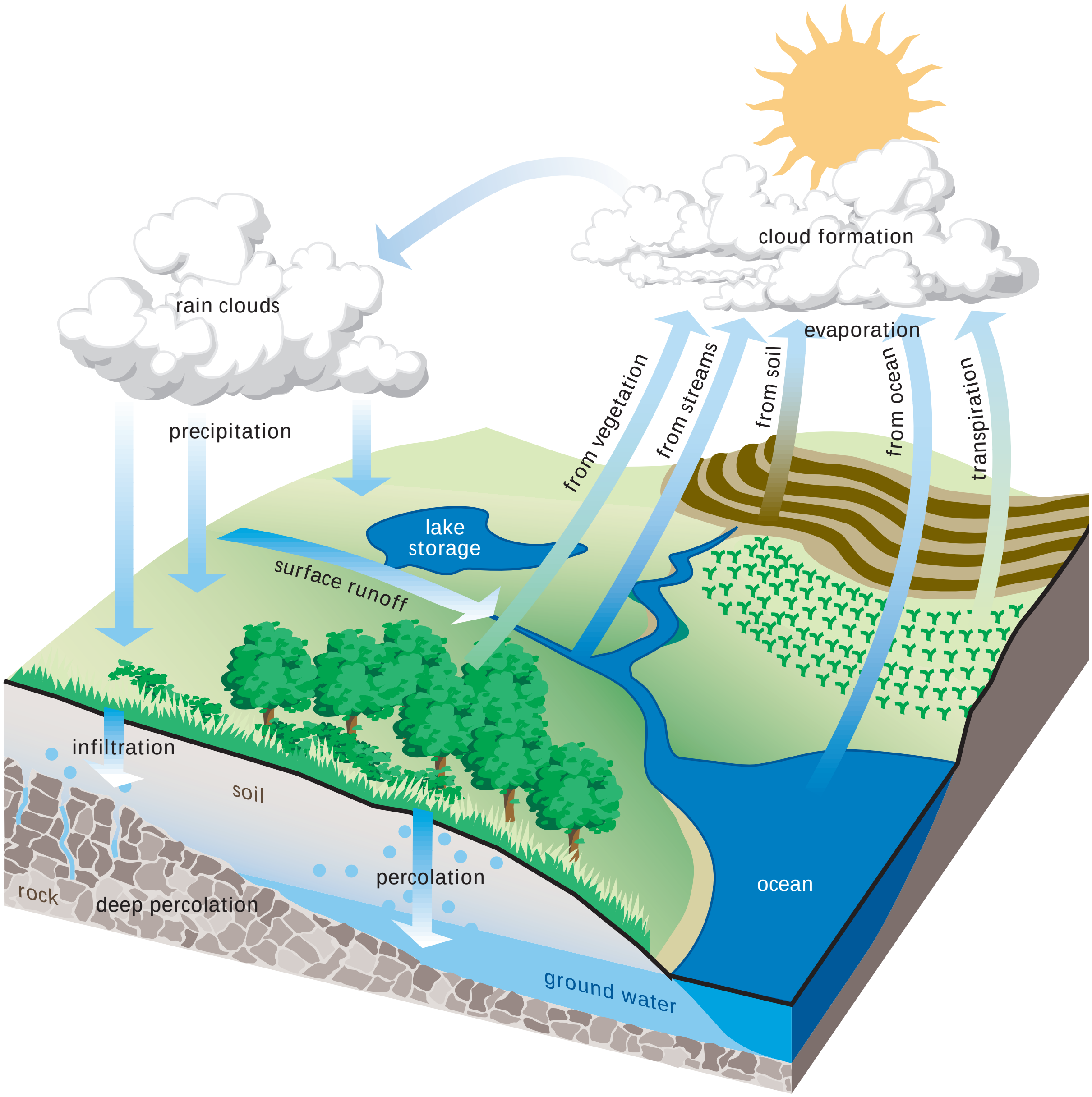
The six major functions of stream corridors are: habitat, conduit, barrier, filter, source, and sink. The integrity of a stream corridor ecosystem depends on how well these functions operate. This section discusses these functions and how they relate to dynamic equilibrium.

2.A Hydrologic and Hydraulic Processes

The hydrologic cycle describes the continuum of the transfer of water from precipitation to surface water and ground water, to storage and runoff, and to the eventual return to the atmosphere by transpiration and evaporation (**Figure 2.2**).

Precipitation returns water to the earth's surface. Although most hydrologic processes are described in terms of rainfall events (or storm events), snowmelt is also an important source of water, especially for rivers that originate in high mountain areas and for continental regions that experience seasonal cycles of snowfall and snowmelt.

Figure 2.2: The hydrologic cycle. *The transfer of water from precipitation to surface water and ground water, to storage and runoff, and eventually back to the atmosphere is an ongoing cycle.*



The type of precipitation that will occur is generally a factor of humidity and air temperature. Topographic relief and geographic location relative to large water bodies also affect the frequency and type of precipitation. Rainstorms occur more frequently along coastal and low-latitude areas with moderate temperatures and low relief. Snowfalls occur more frequently at high elevations and in mid-latitude areas with colder seasonal temperatures.

Precipitation can do one of three things once it reaches the earth. It can return to the atmosphere, move into the soil, or run off the earth's surface into a stream, lake, wetland, or other water body. All three pathways play a role in determining how water moves into, across, and down the stream corridor.

This section is divided into two subsections. The first subsection focuses on hydrologic and hydraulic processes in the lateral dimension, namely, the movement of water from the land into the channel. The second subsection concentrates on water as it moves in the longitudinal dimension, specifically as streamflow in the channel.

Hydrologic and Hydraulic Processes Across the Stream Corridor

Key points in the hydrologic cycle serve as organizational headings in this subsection:

- Interception, transpiration, and evapotranspiration.
- Infiltration, soil moisture, and ground water.
- Runoff.

Interception, Transpiration, and Evapotranspiration

More than two-thirds of the precipitation falling over the United States evaporates to the atmosphere rather than being discharged as streamflow to the oceans. This "short-circuiting" of the hydrologic cycle occurs because of the two processes, interception and transpiration.

Interception

A portion of precipitation never reaches the ground because it is intercepted by vegetation and other natural and constructed surfaces. The amount of water intercepted in this manner is determined by the amount of interception storage available on the above ground surfaces.

In vegetated areas, storage is a function of plant type and the form and density of leaves, branches, and stems (**Table 2.1**). Factors that affect storage in forested areas include:

- Leaf shape. Conifer needles hold water more efficiently than leaves. On leaf surfaces droplets run together and roll off. Needles, however, keep droplets separated.
- Leaf texture. Rough leaves store more water than smooth leaves.
- Time of year. Leafless periods provide less interception potential in the canopy than growing periods; however, more storage sites are created by leaf litter during this time.
- Vertical and horizontal density. The more layers of vegetation that precipitation must penetrate, the less likely it is to reach the soil.
- Age of the plant community. Some vegetative stands become more dense with age; others become less dense.

The intensity, duration, and frequency of precipitation also affect levels of interception.

Figure 2.3 shows some of the pathways rainfall can take in a forest. Rainfall at the beginning of a storm initially fills interception storage sites in the canopy. As the storm continues, water held in these storage sites is displaced. The displaced water drops to the next lower layer of branches and limbs and fills storage sites there. This process is repeated until displaced water reaches the lowest layer, the leaf

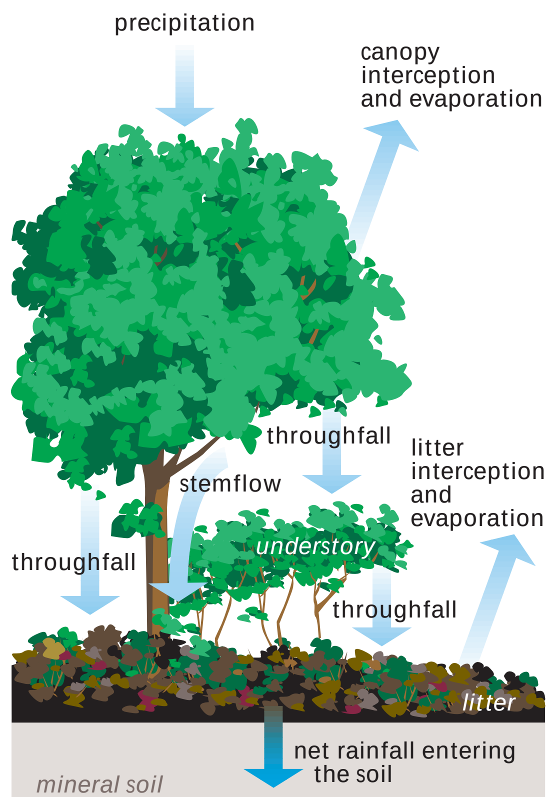
Table 2.1: Percentage of precipitation intercepted for various vegetation types.

Source: Dunne and Leopold 1978.

Vegetative Type	% Precipitation Intercepted
Forests	
Deciduous	13
Coniferous	28
Crops	
Alfalfa	36
Corn	16
Oats	7
Grasses	10-20

Figure 2.3: Typical pathways for forest rainfall.

A portion of precipitation never reaches the ground because it is intercepted by vegetation and other surfaces.



litter. At this point, water displaced off the leaf litter either infiltrates the soil or moves downslope as surface runoff.

Antecedent conditions, such as moisture still held in place from previous storms, affect the ability to intercept and store additional water. Evaporation will eventually remove water residing in interception sites. How fast this process occurs depends on climatic conditions that affect the evaporation rate.

Interception is usually insignificant in areas with little or no vegetation. Bare soil or rock has some small impermeable depressions that function as interception storage sites, but typically most of the precipitation either infiltrates the soil or moves downslope as surface runoff. In areas of frozen soil, interception storage sites are typically filled with frozen water. Consequently, additional rainfall is rapidly transformed into surface runoff.

Interception can be significant in large urban areas. Although urban drainage systems are designed to quickly move storm water off impervious surfaces, the urban landscape is rich with storage sites. These include flat rooftops, parking lots, potholes, cracks, and other rough surfaces that can intercept and hold water for eventual evaporation.

Transpiration and Evapotranspiration

Transpiration is the diffusion of water vapor from plant leaves to the atmosphere. Unlike intercepted water, which originates from precipitation, transpired water originates from water taken in by roots.

Transpiration from vegetation and evaporation from interception sites and open water surfaces, such as ponds and lakes, are not the only sources of water returned to the atmosphere. Soil moisture also is subject to evaporation. Evaporation of soil moisture is, however, a much slower process due to capillary and osmotic forces that keep the moisture in the soil and the fact that vapor must diffuse upward through soil pores to reach surface air at a lower vapor pressure.

Because it is virtually impossible to separate water loss due to transpiration from water loss due to evaporation, the two processes are commonly combined and labeled *evapotranspiration*. Evapotranspiration can dominate the water balance and can control soil moisture content, ground water recharge, and streamflow.

The following concepts are important when describing evapotranspiration:

- If soil moisture conditions are limiting, the actual rate of evapotranspiration is below its potential rate.
- When vegetation loses water to the atmosphere at a rate unlimited by the supply of water replenishing the roots, its actual rate of evapotranspiration is equal to its potential rate of evapotranspiration.

The amount of precipitation in a region drives both processes, however. Soil types and rooting characteristics also play important roles in determining the actual rate of evapotranspiration.

Evaporation

Water is subject to evaporation whenever it is exposed to the atmosphere. Basically this process involves:

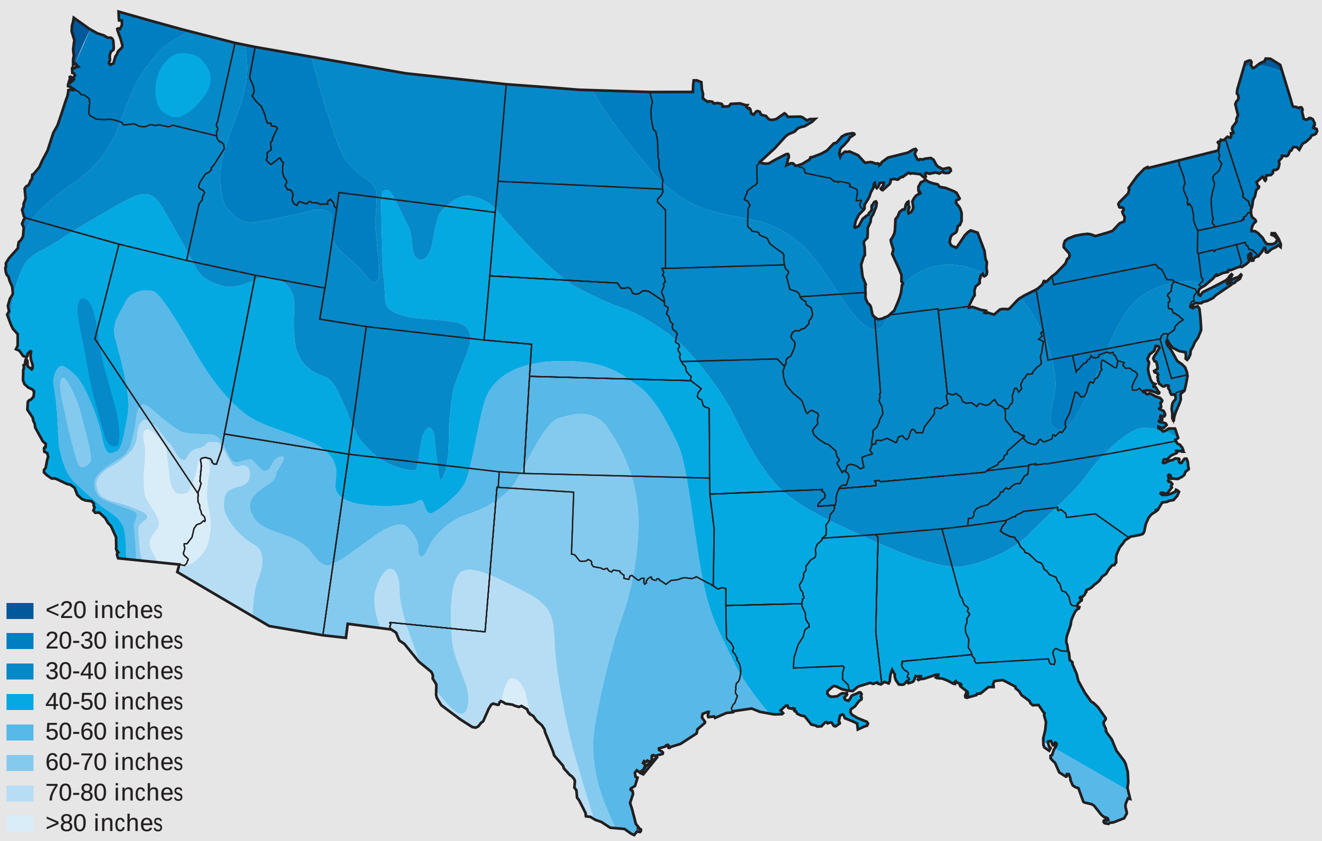
- The change of state of water from liquid to vapor
- The net transfer of this vapor to the atmosphere

The process begins when some molecules in the liquid state attain sufficient kinetic energy (primarily from solar energy) to overcome the forces of surface tension and move into the atmosphere. This movement creates a vapor pressure in the atmosphere.

The net rate of movement is proportional to the difference in vapor pressure between the water surface and the atmosphere above that surface. Once the pressure is equalized, no more evaporation can occur until new air, capable of holding more water vapor, displaces the old saturated air. Evaporation rates therefore vary according to latitude, season, time of day, cloudiness, and wind energy. Mean annual lake evaporation in the United States, for example, varies from 20 inches in Maine and Washington to about 86 inches in the desert Southwest (**Figure 2.4**).

Figure 2.4: Mean annual lake evaporation for the period 1946-1955.

(From Dunne and Leopold (1978) modified from Kohler et al. (1959).)



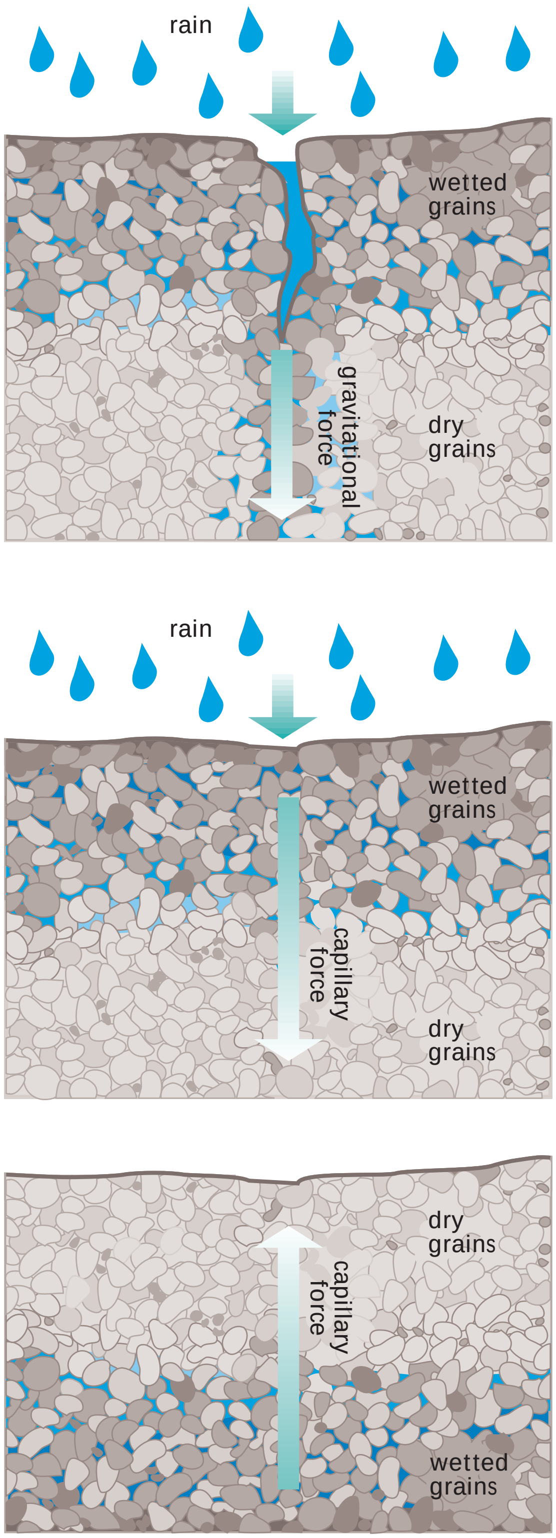


Figure 2.5: Soil profile. *Water is drawn into the pores in soil by gravity and capillary action.*

Infiltration, Soil Moisture, and Ground Water

Precipitation that is not intercepted or flows as surface runoff moves into the soil. Once there, it can be stored in the upper layer or move downward through the soil profile until it reaches an area completely saturated by water called the *phreatic zone*.

Infiltration

Close examination of the soil surface reveals millions of particles of sand, silt, and clay separated by channels of different sizes (**Figure 2.5**). These macropores include cracks, “pipes” left by decayed roots and wormholes, and pore spaces between lumps and particles of soil.

Water is drawn into the pores by gravity and capillary action. Gravity is the dominant force for water moving into the largest openings, such as worm or root holes. Capillary action is the dominant force for water moving into soils with very fine pores.

The size and density of these pore openings determine the water’s rate of entry into the soil. *Porosity* is the term used to describe the percentage of the total soil volume taken up by spaces between soil particles. When all those spaces are filled with water, the soil is said to be saturated.

Soil characteristics such as texture and tilth (looseness) are key factors in determining porosity. Coarse-textured, sandy soils and soils with loose aggregates held together by organic matter or small amounts of clay have large pores and, thus, high porosity. Soils that are tightly packed or clayey have low porosity.

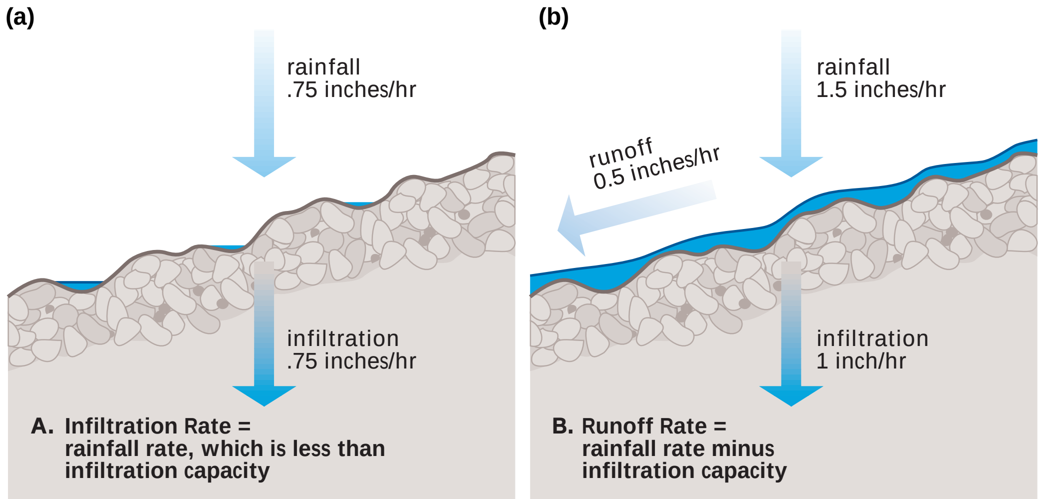


Figure 2.6: Infiltration and runoff. *Surface runoff occurs when rainfall intensity exceeds infiltration capacity.*

Infiltration is the term used to describe the movement of water into soil pores. The *infiltration rate* is the amount of water that soaks into soil over a given length of time. The maximum rate that water infiltrates a soil is known as the soil's *infiltration capacity*.

If rainfall intensity is less than infiltration capacity, water infiltrates the soil at a rate equal to the rate of rainfall. If the rainfall rate exceeds the infiltration capacity, the excess water either is detained in small depressions on the soil surface or travels downslope as surface runoff (**Figure 2.6**).

The following factors are important in determining a soil's infiltration rate:

- Ease of entry through the soil surface.
- Storage capacity within the soil.
- Transmission rate through the soil.

Areas with natural vegetative cover and leaf litter usually have high infiltration rates. These features protect the surface soil pore spaces from being plugged by fine soil particles created by raindrop splash. They also provide habitat for worms and other burrowing organisms and provide organic matter that helps bind fine soil particles together. Both of these processes increase porosity and the infiltration rate.

The rate of infiltration is not constant throughout the duration of a storm. The rate is usually high at the beginning of a storm but declines rapidly as gravity-fed storage capacity is filled. A slower, but stabilized, rate of infiltration is reached typically 1 or 2 hours into a storm. Several factors are involved in this stabilization process, including the following:

- Raindrops breaking up soil aggregates and producing finer material, which then blocks pore openings on the surface and reduces the ease of entry.
- Water filling fine pore spaces and reducing storage capacity.

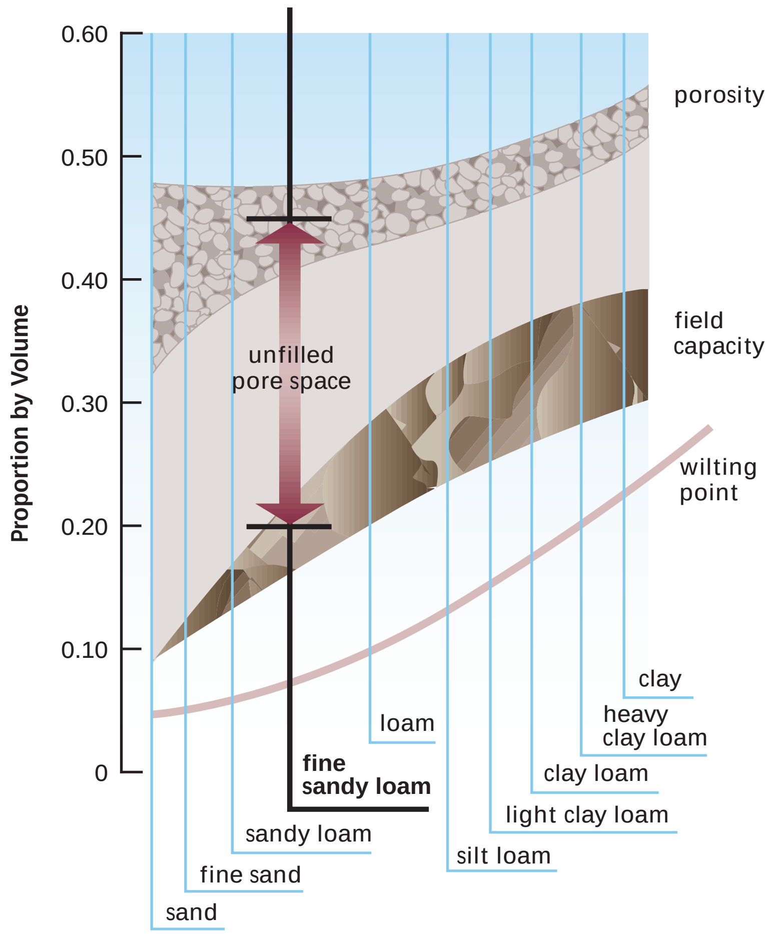


Figure 2.7: Water-holding properties of various soils

Water-holding properties vary by texture. For a fine sandy loam the approximate difference between porosity, 0.45, and field capacity, 0.20, is 0.25, meaning that the unfilled pore space is 0.25 times the soil volume. The difference between field capacity and wilting point is a measure of unfilled pore space.

Source: Dunne and Leopold 1978.

- Wetted clay particles swelling and effectively reducing the diameter of pore spaces, which, in turn, reduces transmission rates.

Soils gradually drain or dry following a storm. However, if another storm occurs before the drying process is completed, there is less storage space for new water. Therefore, antecedent moisture conditions are important when analyzing available storage.

Soil Moisture

After a storm passes, water drains out of upper soils due to gravity. The soil remains moist, however, because some amount of water remains tightly held in fine pores and around particles by surface tension. This condition, called *field capacity*, varies with soil texture. Like porosity, it is expressed as a proportion by volume.

The difference between porosity and field capacity is a measure of unfilled pore space (**Figure 2.7**). Field capacity is an approximate number, however, because gravitation drainage continues in moist soil at a slow rate.

Soil moisture is most important in the context of evapotranspiration. Terrestrial plants depend on water stored in soil. As their roots extract water from progressively finer pores, the moisture content in the soil may fall below the field capacity. If soil moisture is not replenished, the roots eventually reach a point where they cannot create enough suction to extract the tightly held interstitial pore water. The moisture content of the soil at this point, which varies depending on soil characteristics, is called the *permanent wilting point* because plants can no longer withdraw water from the soil at a rate high enough to keep up with the demands of transpiration, causing the plants to wilt.

Deep percolation is the amount of water that passes below the root zone of crops, less any upward movement of water from below the root zone (Jensen et al. 1990).

Ground Water

The size and quantity of pore openings also determines the movement of water within the soil profile. Gravity causes water to move vertically downward. This movement occurs easily through larger pores. As pores reduce in size due to swelling of clay particles or filling of pores, there is a greater resistance to flow. Capillary forces eventually take over and cause water to move in any direction.

Water will continue to move downward until it reaches an area completely saturated with water, the *phreatic zone* or zone of saturation (**Figure 2.8**). The top of the phreatic zone defines the *ground water table* or phreatic surface. Just above the ground water table is an area called the *capillary fringe*, so named because the pores in this area are filled with water held by capillary forces.

In soils with tiny pores, such as clay or silt, the capillary forces are strong. Consequently, the capillary fringe can extend a large distance upward from the water table. In sandstone or soils

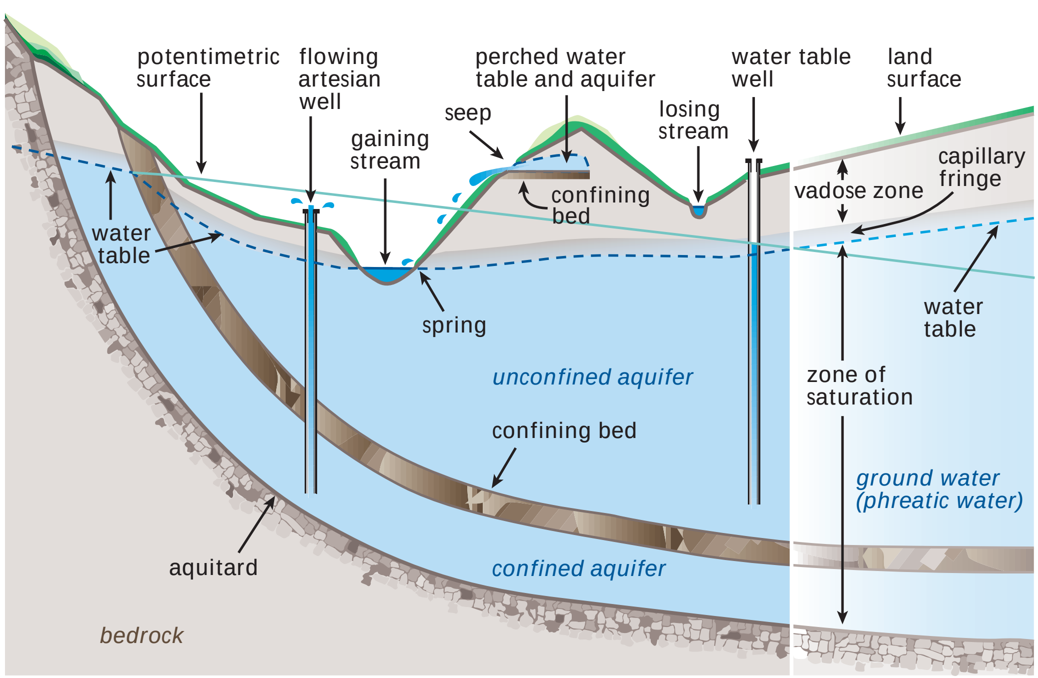


Figure 2.8: Ground water related features and terminology.
Ground water elevation along the stream corridor can vary significantly over short distances, depending on subsurface characteristics.

with large pores, the capillary forces are weak and the fringe narrow.

Between the capillary fringe and the soil surface is the *vadose zone*, or the zone of aeration. It contains air and microbial respiratory gases, capillary water, and water moving downward by gravity to the phreatic zone. *Pellicular water* is the film of ground water that adheres to individual particles above the ground water table. This water is held above the capillary fringe by molecular attraction.

If the phreatic zone provides a consistent supply of water to wells, it is known as an *aquifer*. Good aquifers usually have a large lateral and vertical extent relative to the amount of water withdrawn from wells and high porosity, which allows water to drain easily.

The opposite of an aquifer is an aquitard or confining bed. *Aquitards* or *confining beds* are relatively thin sediment or rock layers that have low permeability. Vertical water movement through an aquitard is severely restricted. If an aquifer has no confining layer overlying it, it is known as an *unconfined aquifer*. A *confined aquifer* is one confined by an aquitard.

The complexity and diversity of aquifers and aquitards result in a multitude of underground scenarios. For example, *perched ground water* occurs when a shallow aquitard of limited size prevents water from moving down to the phreatic zone. Water collects above the aquitard and forms a “mini-phreatic zone.” In many cases, perched ground water appears only during a storm or during the wet season. Wells tapping perched ground water may experience a shortage of water during the dry season. Perched aquifers can, however, be important local sources of ground water.

Artesian wells are developed in confined aquifers. Because the hydrostatic pressure in confined aquifers is greater than atmospheric pressure, water levels in artesian wells rise to a level where atmospheric pressure equals hydrostatic pressure. If this elevation is above the ground surface, water can flow freely out of the well.

Water also will flow freely where the ground surface intersects a confined aquifer. The *piezometric surface* is the level to which water would rise in wells tapped into confined aquifers if the wells extended indefinitely above the ground surface. Phreatic wells draw water from below the phreatic zone in unconfined aquifers. The water level in a phreatic well is the same as the ground water table.

Practitioners of stream corridor restoration should be concerned with locations where ground water and surface water are exchanged. Areas that freely allow movement of water to the phreatic zone are called *recharge areas*. Areas where the water table meets the soil surface or where stream and ground water emerge are called *springs* or *seeps*.

The volume of ground water and the elevation of the water table fluctuate according to ground water recharge and discharge. Because of the fluctuation of water table elevation, a stream channel can function either as a recharge area (influent or “losing” stream) or a discharge area (effluent or “gaining” stream).

Runoff

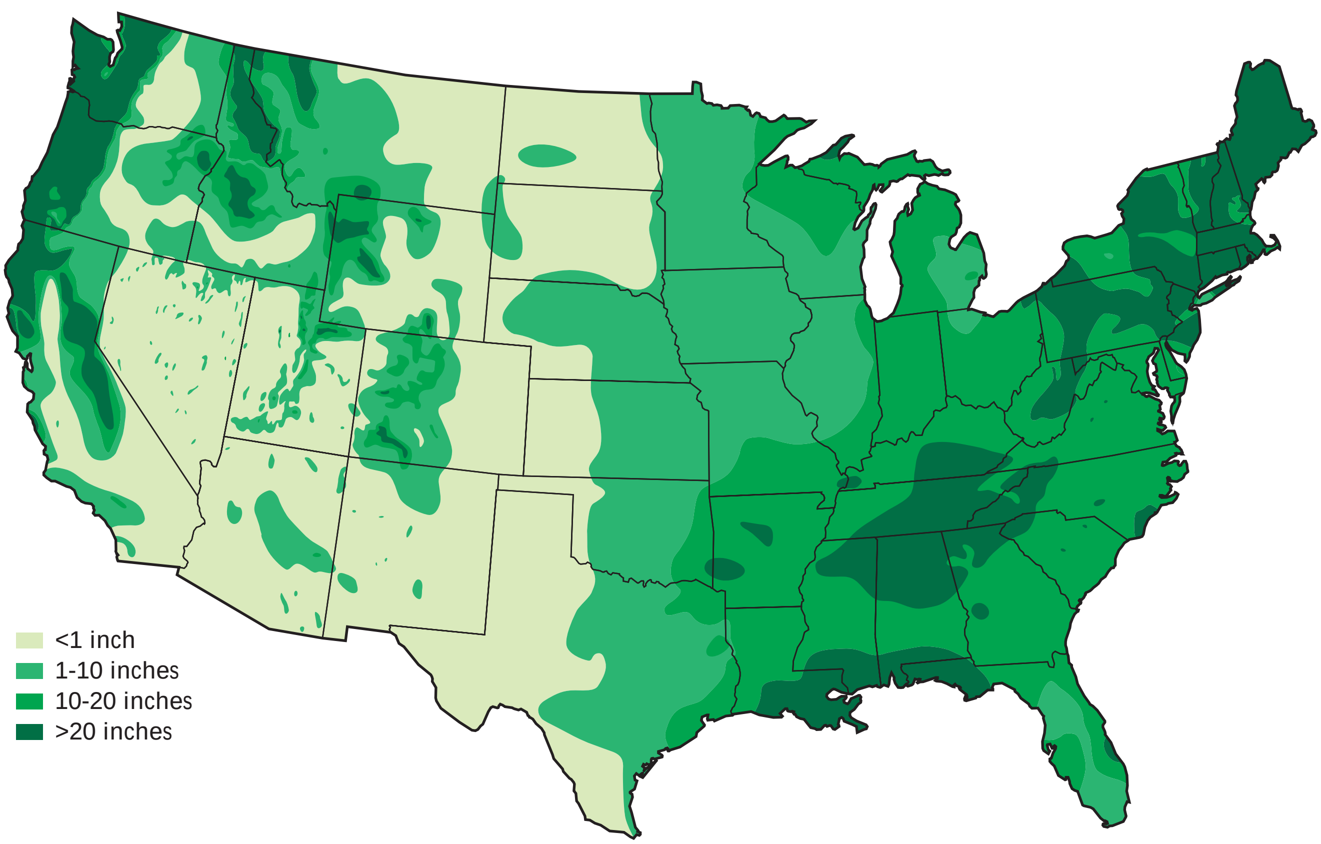
When the rate of rainfall or snowmelt exceeds infiltration capacity, excess water collects on the soil surface and travels downslope as runoff. Factors that affect runoff processes include climate, geology, topography, soil characteristics, and vegetation. Average annual runoff in the contiguous United States ranges from less than 1 inch to more than 20 inches (**Figure 2.9**).

Three basic types of runoff are introduced in this subsection (**Figure 2.10**):

- Overland flow
- Subsurface flow
- Saturated overland flow

Each of these runoff types can occur individually or in some combination in the same locale.

Figure 2.9: Average annual runoff in the contiguous United States.
Average annual runoff varies with regions.
Source: USGS 1986.



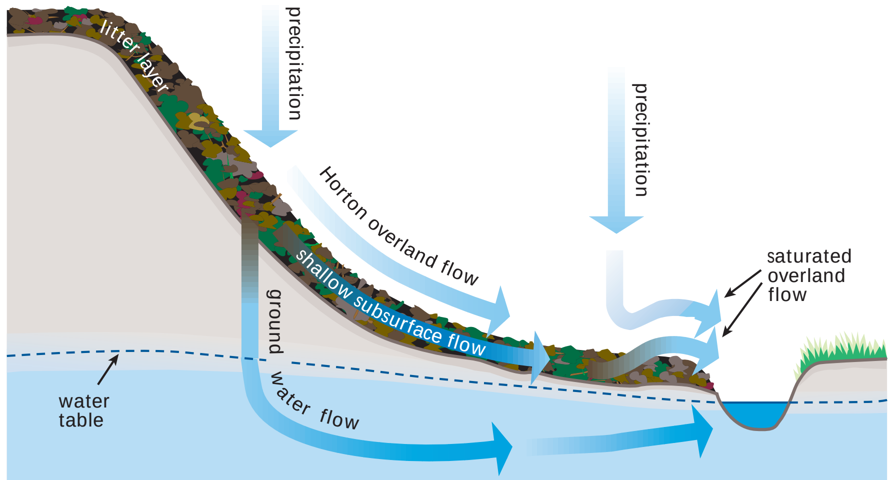


Figure 2.10: Flow paths of water over a surface.
The portion of precipitation that runs off or infiltrates to the ground water table depends on the soil's permeability rate, surface roughness, and the amount, duration, and intensity of precipitation.

Overland Flow

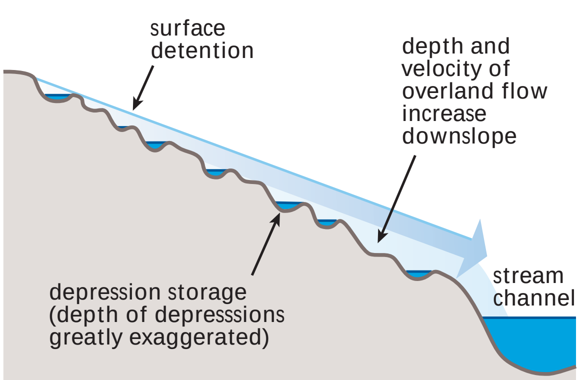
When the rate of precipitation exceeds the rate of infiltration, water collects on the soil surface in small depressions (**Figure 2.11**). The water stored in these spaces is called *depression storage*. It eventually is returned to the atmosphere through evaporation or infiltrates the soil surface.

After depression storage spaces are filled, excess water begins to move downslope as overland flow, either as a shallow sheet of water or as a series of small rivulets or rills. Horton (1933) was the first to describe this process in the literature. The term *Horton overland flow* or Hortonian flow is commonly used.

The sheet of water increases in depth and velocity as it moves downhill. As it travels, some of the overland flow is trapped on the hillside and is called *surface detention*. Unlike depression storage, which evaporates to the atmosphere or enters the soil, surface detention is only temporarily detained from its journey downslope. It eventually runs off into the stream and is still considered part of the total volume of overland flow.

Overland flow typically occurs in urban and suburban settings with paved and impermeable surfaces. Paved areas and soils that have been exposed and compacted by heavy equipment or vehicles are also prime settings for overland flow. It is also common in areas of thin soils with sparse vegetative cover such as in mountainous terrain of arid or semi-arid regions.

Figure 2.11: Overland flow and depression storage.
Overland moves downslope as an irregular sheet.
Source: Dunne and Leopold 1978.



Subsurface Flow

Once in the soil, water moves in response to differences in hydraulic head (the potential for flow due to the gradient of hydrostatic pressure at different elevations). Given a simplified situation, the water table before a rainstorm has a parabolic surface that slopes toward a stream. Water moves downward and along this slope and into the stream channel. This portion of the flow is the baseflow. The soil below the water table is, of course, saturated. Assuming the hill slope has uniform soil characteristics, the moisture content of surface soils diminishes with distance from the stream.

During a storm, the soil nearest the stream has two important attributes as compared to soil upslope—a higher moisture content and a shorter distance to the water table. These attributes cause the water table to rise more rapidly in response to rainwater infiltration and causes the water table to steepen. Thus a new, storm-generated ground water component is added to baseflow. This new component, called *subsurface flow*, mixes with baseflow and increases ground water discharge to the channel.

In some situations, infiltrated storm water does not reach the phreatic zone because of the presence of an aquitard. In this case, subsurface flow does not mix with baseflow, but also discharges water into the channel. The net result, whether mixed or not, is increased channel flow.

Saturated Overland Flow

If the storm described above continues, the slope of the water table surface can continue to steepen near the stream. Eventually, it can steepen to the point that the water table rises above the channel elevation. Additionally, ground water can break out of the soil and travel to the stream as overland flow. This type of runoff is termed *quick return flow*.

The soil below the ground water breakout is, of course, saturated. Consequently, the maximum infiltration rate is reached, and all of the rain falling on it flows downslope as overland runoff. The combination of this direct precipitation and quick return flow is called *saturated overland flow*. As the storm progresses, the saturated area expands further up the hillside. Because quick return flow and subsurface flow are so closely linked to overland flow, they are normally considered part of the overall runoff of surface water.

Hydrologic and Hydraulic Processes Along the Stream Corridor

Water flowing in streams is the collection of direct precipitation and water that has moved laterally from the land into the channel. The amount and timing of this lateral movement directly influences the amount and timing of streamflow, which in turn influences ecological functions in the stream corridor.

Flow Analysis

Flows range from no flow to flood flows in a variety of time scales. On a broad scale, historical climate records reveal occasional persistent periods of wet and dry years. Many rivers in the United States, for example, experienced a decline in flows during the

FAST FORWARD

More detailed information about flow duration and frequency is presented in ***Chapter 7, Section A****.*

"dust bowl" decade in the 1930s. Another similar decline in flows nationwide occurred in the 1950s. Unfortunately, the length of record regarding wet and dry years is short (in geologic time), making it is difficult to predict broad-scale persistence of wet or dry years.

Seasonal variations of streamflow are more predictable, though somewhat complicated by persistence factors. Because design work requires using historical information (period of record) as a basis for designing for the future, flow information is usually presented in a probability format. Two formats are especially useful for planning and designing stream corridor restoration:

- *Flow duration*, the probability a given streamflow was equaled or exceeded over a period of time.
- *Flow frequency*, the probability a given streamflow will be exceeded (or not exceeded) in a year. (Sometimes this concept is modified and expressed as the average number of years between exceeding [or not exceeding] a given flow.)

Figure 2.12: An example of monthly probability curves

Monthly probability that the mean monthly discharge will be less than the values indicated. Yakima River near Parker, Washington (Data from US Army Corps of Engineers)

Source: Dunne and Leopold 1978.

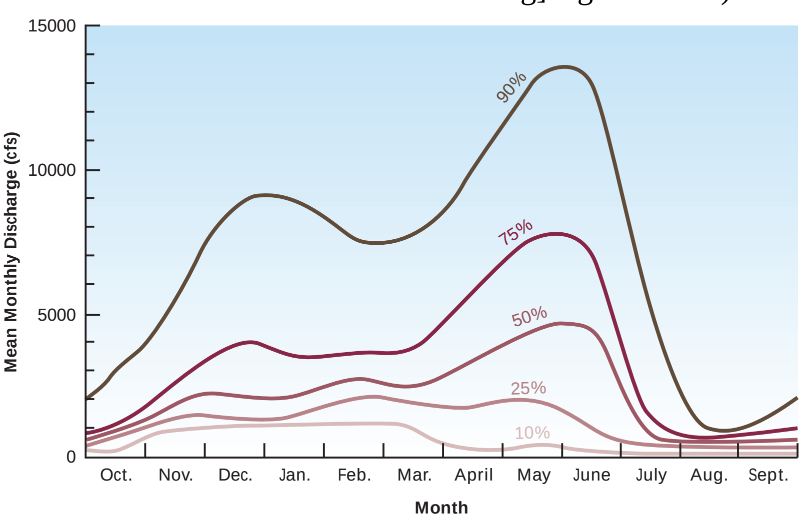


Figure 2.12 presents an example of a flow frequency expressed as a series of probability curves. The graph displays months on the x-axis and a range of mean monthly discharges on the y-axis. The curves indicate the probability that the mean monthly discharge will be less than the value indicated by the curve. For example, on about January 1, there is a 90 percent chance that the discharge will be less than 9,000 cfs and a 50 percent chance it will be less than 2,000 cfs.

Ecological Impacts of Flow

The variability of streamflow is a primary influence on the biotic and abiotic processes that determine the structure and dynamics of stream ecosystems (Covich 1993). High flows are important not only in terms of sediment transport, but also in terms of reconnecting floodplain wetlands to the channel.

This relationship is important because floodplain wetlands provide spawning and nursery habitat for fish and, later in the year, foraging habitat for waterfowl. Low flows, especially in large rivers, create conditions that allow tributary fauna to disperse, thus maintaining populations of a single species in several locations.

In general, completion of the life cycle of many riverine species requires an array of different habitat types whose temporal availability is determined by the flow regime. Adaptation to this environmental dynamism allows riverine species to persist during periods of droughts and floods that destroy and recreate habitat elements (Poff et al. 1997).

2.B Geomorphic Processes

Geomorphology is the study of surface forms of the earth and the processes that developed those forms. The hydrologic processes discussed in the previous section drive the geomorphic processes described in this section. In turn, the geomorphic processes are the primary mechanisms for forming the drainage patterns, channel, floodplain, terraces, and other watershed and stream corridor features discussed in Chapter 1.

Three primary geomorphic processes are involved with flowing water, as follows:

- *Erosion*, the detachment of soil particles.
- *Sediment transport*, the movement of eroded soil particles in flowing water.
- *Sediment deposition*, settling of eroded soil particles to the bottom of a water body or left behind as water leaves. Sediment deposition can be transitory, as in a stream channel from one storm to another, or more or less permanent, as in a larger reservoir.

Since geomorphic processes are so closely related to the movement of water, this section is organized into subsections that mirror the hydrologic processes of surface storm water runoff and streamflow:

- Geomorphic Processes Across the Stream Corridor
- Geomorphic Processes Along the Stream Corridor

Geomorphic Processes Across the Stream Corridor

The occurrence, magnitude, and distribution of erosion processes in watersheds affect the yield of sediment and associated water quality contaminants to the stream corridor.

Soil erosion can occur gradually over a long period, or it can be cyclic or episodic, accelerating during certain seasons or during certain rainstorm events (**Figure 2.13**). Soil erosion can be caused by human actions or by natural processes. Erosion is not a simple process because soil conditions are continually changing with temperature, moisture content, growth stage and amount of vegetation, and the human manipulation of the soil for development or crop production.

Figure 2.13: Raindrop impact.
One of many types of erosion.

Table 2.2: Erosion processes.

Agent	Process
Raindrop impact	Sheet, interill
Surface water runoff	Sheet, interill, rill, ephemeral gully, classic gully
Channelized flow	Rill, ephemeral gully, classic gully, wind, streambank
Gravity	Classic gully, streambank, landslide, mass wasting
Wind	Wind
Ice	Streambank, lake shore
Chemical reactions	Solution, dispersion

Table 2.3: Erosion types vs. physical processes.

	Erosion/Physical Process			
Erosion Type	Sheet	Concentrated Flow	Mass Wasting	Combination
Sheet and rill	x	x		
Interill	x			
Rill	x	x		
Wind	x	x		
Ephemeral gully		x		
Classic gully		x	x	
Floodplain scour		x		
Roadside				x
Streambank		x	x	
Streambed		x		
Landslide			x	
Wave/shoreline				x
Urban, construction				x
Surface mine				x
Ice gouging				x

Tables 2.2 and 2.3 show the basic processes that influence soil erosion and the different types of erosion found within the watershed.

Geomorphic Processes Along the Stream Corridor

The channel, floodplain, terraces, and other features in the stream corridor are formed primarily through the erosion, transport, and deposition of sediment by streamflow. This subsection describes the processes involved with transporting sediment loads downstream and how the channel and floodplain adjust and evolve through time.

Sediment Transport

Sediment particles found in the stream channel and floodplain can be categorized according to size. A boulder is the largest particle and clay is the smallest particle. Particle density depends on the size and composition of the particle (i.e., the specific gravity of the mineral content of the particle).

No matter the size, all particles in the channel are subject to being transported downslope or downstream. The size of the largest particle a stream can move under a given set of hydraulic conditions is referred to as *stream competence*. Often, only very high flows are competent to move the largest particles.

Closely related to stream competence is the concept of *tractive stress*, which creates lift and drag forces at the stream boundaries along the bed and banks. Tractive stress, also known as *shear stress*, varies as a function of flow depth and slope. Assuming constant density, shape, and surface roughness, the larger the particle, the greater the amount of tractive stress needed to dislodge it and move it downstream.

The energy that sets sediment particles into motion is derived from the effect of faster water flowing past slower water. This velocity gradient happens because the water in the main body of flow moves faster than water flowing at the boundaries. This is because boundaries are rough and create friction as flow moves over them which, in turn, slows flow.

The momentum of the faster water is transmitted to the slower boundary water. In doing so, the faster water tends to roll up the slower water in a spiral motion. It is this shearing motion, or shear stress, that also moves bed particles in a rolling motion downstream.

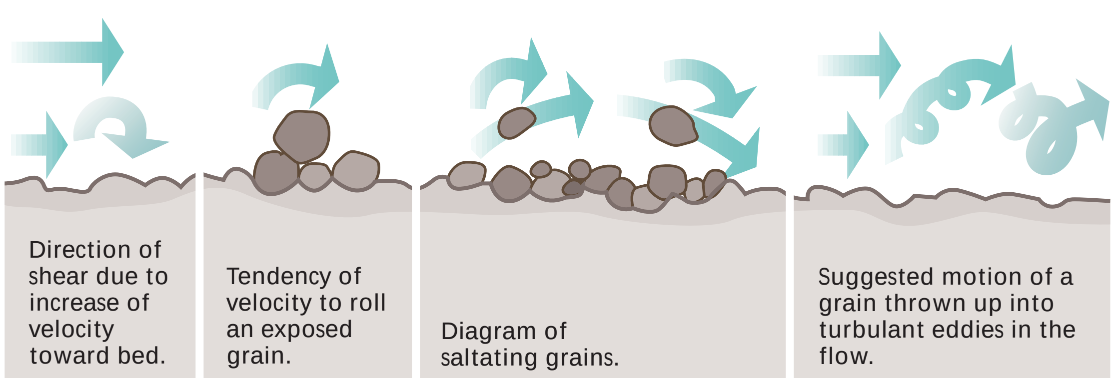
Particle movement on the channel bottom begins as a sliding or rolling motion, which transports particles along the streambed in the direction of flow (**Figure 2.14**). Some particles also may move above the bed surface by *saltation*, a skipping motion that occurs when one particle collides with another particle, causing it to bounce upward and then fall back toward the bed.

These rolling, sliding, and skipping motions result in frequent contact of the moving particles with the streambed and characterize the set of moving particles known as *bed load*. The weight of these particles relative to flow velocity causes them essentially to remain in contact with, and to be supported by, the streambed as they move downstream.

Finer-grained particles are more easily carried into suspension by turbulent eddies. These particles are transported within the water column and are therefore called the *suspended load*. Although there may be continuous exchange of sediment between the bed load and suspended load of the river, as long as sufficient turbulence is present.

Part of the suspended load may be colloidal clays, which can remain in suspension for very long time periods, depending on the type of clay and water chemistry.

Figure 2.14: Action of water on particles near the streambed.
Processes that transport bed load sediments are a function of flow velocities, particle size, and principles of hydrodynamics.
From: Water in Environmental Planning by Dunne and Leopold © 1978 by W.H. Freeman and Company. Used with permission.



Sediment Transport Terminology

Sediment transport terminology can sometimes be confusing. Because of this confusion, it is important to define some of the more frequently used terms.

- *Sediment load*, the quantity of sediment that is carried past any cross section of a stream in a specified period of time, usually a day or a year. *Sediment discharge*, the mass or volume of sediment passing a stream cross section in a unit of time. Typical units for sediment load are tons, while sediment discharge units
- *Bed-material load*, part of the total sediment discharge that is composed of sediment particles that are the same size as streambed sediment.
- *Wash load*, part of the total sediment load that is comprised of particle sizes finer than those found in the streambed.
- *Bed load*, portion of the total sediment load that moves on or near the streambed by saltation, rolling, or sliding in the bed layer.
- *Suspended bed material load*, portion of the bed material load that is transported in suspension in the water column. The suspended bed material load and the bed load comprise the total bed material load.
- *Suspended sediment discharge* (or *suspended load*), portion of the total sediment load that is transported in suspension by turbulent fluctuations within the body of flowing water.
- *Measured load*, portion of the total sediment load that is obtained by the sampler in the sampling zone.
- *Unmeasured load*, portion of the total sediment load that passes beneath the sampler, both in suspension and on the bed. With typical suspended sediment samplers this is the lower 0.3 to 0.4 feet of the vertical.

The above terms can be combined in a number of ways to give the total sediment load in a stream **(Table 2.4)**. However, it is important not to combine terms that are not compatible. For example, the suspended load and the bed material load are not complimentary terms because the suspended load may include a portion of the bed material load, depending on the energy available for transport. The total sediment load is correctly defined by the combination of the following terms:

Total Sediment Load =

Bed Material Load + Wash Load

or

Bed Load + Suspended Load

or

Measured Load + Unmeasured Load

Table 2.4: Sediment load terms.

		Classification System	
		Based on Mechanism of Transport	Based on Particle Size
Total sediment load	**Wash load**	Suspended load	Wash load
	Suspended bed-material load		Bed-material load
	Bed load	Bed load	

Sediment transport rates can be computed using various equations or models. These are discussed in the *Stream Channel Restoration* section of Chapter 8.

Stream Power

One of the principal geomorphic tasks of a stream is to transport particles out of the watershed (**Figure 2.15**). In this manner, the stream functions as a transporting "machine;" and, as a machine, its rate of doing work can be calculated as the product of available power multiplied by efficiency.

Stream power can be calculated as:

$$\varphi = \gamma Q S$$

Where:

φ = Stream power (foot-lbs/second-foot)

γ = Specific weight of water (lbs/ft^3)

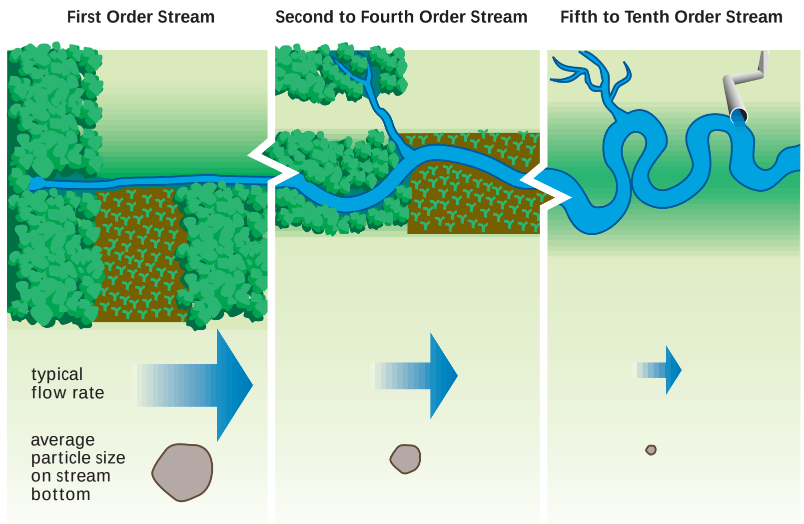
Q = Discharge (ft^3/second)

S = Slope (feet/feet)

Sediment transport rates are directly related to stream power; i.e., slope and discharge. Baseflow that follows the highly sinuous thalweg (the line that marks the deepest points along the stream channel) in a meandering stream generates little stream power; therefore, the stream's ability to move sediment, *sediment-transport capacity* is limited. At higher depths, the flow follows a straighter course, which increases slope, causing increased sediment transport rates. The stream builds its cross section to obtain depths of flow and channel slopes that generate the sediment-transport capacity needed to maintain the stream channel.

Figure 2.15: Particle transport.

A stream's total sediment load in the total of all sediment particles moving past a defined cross section over a specified time period. Transport rates vary according to the mechanism of transport.



Wash Load and Bed-Material Load

One way to differentiate the sediment load of a stream is to characterize it based on the immediate source of the sediment in transport. The total sediment load in a stream, at any given time and location, is divided into two parts - wash load and bed-material load. The primary source of wash load is the watershed, including sheet and rill erosion, gully erosion, and upstream streambank erosion. The source of bed material load is primarily the streambed itself, but includes other sources in the watershed.

Wash load is composed of the finest sediment particles in transport. Turbulence holds the wash load in suspension. The concentration of wash load in suspension is essentially independent of hydraulic conditions in the stream and therefore cannot be calculated using measured or estimated hydraulic parameters such as velocity or discharge. Wash load concentration is normally a function of supply; i.e., the stream can carry as much wash load as the watershed and banks can deliver (for sediment concentrations below approximately 3000 parts per million)

Bed-material load is composed of the sediment of size classes found in the streambed. Bed-material load moves along the streambed by rolling, sliding, or jumping, and may be periodically entrained into the flow by turbulence, where it becomes a portion of the suspended load. Bed-material load is hydraulically controlled and can be computed using sediment transport equations discussed in Chapter 8.

Runoff can vary from a watershed, either due to natural causes or land use practices. These variations may change the size distribution of sediments delivered to the stream from the watershed by preferentially moving particular particle sizes into the stream. It is not uncommon to find a layer of sand on top of a cobble layer . This often happens when accelerated erosion of sandy soils occurs in a watershed and the increased load of sand exceeds the transport capacity of the stream during events that move the sand into the channel.

Stream and Floodplain Stability

A question that normally arises when considering any stream restoration action is “Is it stable now and will it be stable after changes are made?” The answer may be likened to asking an opinion on a movie based on only a few frames from the reel. Although we often view streams based on a limited reference with respect to time, it is important that we consider the long-term changes and trends in channel cross section, longitudinal profile, and planform morphology to characterize channel stability.

Achieving channel stability requires that the average tractive stress maintains a stable streambed and streambanks. That is, the distribution of particle sizes in each section of the stream remains in equilibrium (i.e., new particles deposited are the same size and shape as particles displaced by tractive stress).

Yang (1971) adapted the basic theories described by Leopold to explain the longitudinal profile of rivers, the formation of stream networks, riffles, and pools, and river meandering. All these river characteristics and sediment transport are closely related. Yang (1971) developed the theory of average stream fall and the theory of least rate of energy expenditure, based on the entropy concept. These theories state that during the evolution toward an equilibrium condition, a natural stream chooses its course of flow in such a manner that the rate of potential energy expenditure per unit mass of flow along its course is a minimum.

Corridor Adjustments

Stream channels and their floodplains are constantly adjusting to the water and sediment supplied by the watershed. Successful restoration of degraded streams requires an understanding of watershed history, including both natural events and land use practices, and the adjustment processes active in channel evolution.

Channel response to changes in water and sediment yield may occur at differing times and locations, requiring various levels of energy expenditure. Daily changes in streamflow and sediment load result in frequent adjustment of bedforms and roughness in many streams with movable beds. Streams also adjust periodically to extreme high- and low-flow events, as floods not only remove vegetation but create and increase vegetative potential along the stream corridor (e.g., low flow periods allow vegetation incursion into the channel).

Similar levels of adjustment also may be brought about by changes in land use in the stream corridor and the upland watershed. Similarly, long-term changes in runoff or sediment yield from natural causes, such as climate change, wildfire, etc., or human causes, such as cultivation, overgrazing, or rural-to-urban conversions, may lead to long-term adjustments in channel cross section and planform that are frequently described as channel evolution.

Stream channel response to changes in flow and sediment load have been described qualitatively in a number of studies (e.g., Lane 1955, Schumm 1977). As discussed in Chapter 1, one of the earliest relationships proposed for explaining stream behavior was suggested by Lane (1955), who related mean annual streamflow (Q_w) and channel slope (S) to bed-material sediment load (Q_s) and median particle size on the streambed (D_{50}):

$$Q_s \bullet D_{50} \sim Q_w \bullet S$$

Lane's relationship suggests that a channel will be maintained in dynamic equilibrium when changes in sediment load and bed-material size are balanced by changes in streamflow or channel gradient. A change in one of these variables causes changes in one or more of the other variables such that dynamic equilibrium is reestablished.

Additional qualitative relationships have been proposed for interpreting behavior of alluvial channels. Schumm (1977) suggested that width (b), depth (d), and meander wavelength (L) are directly proportional, and that channel gradient (S) is inversely proportional to streamflow (Q_w) in an alluvial channel:

$$Q_w \sim \frac{b,\ d,\ L}{S}$$

Schumm (1977) also suggested that width (b), meander wavelength (L), and channel gradient (S) are directly proportional, and that depth (d) and sinuosity (P) are inversely proportional to sediment discharge (Q_s) in alluvial streams:

$$Q_s \sim \frac{b,\ L,\ S}{d,\ P}$$

The above two equations may be rewritten to predict direction of change in channel characteristics, given an increase or decrease in streamflow or sediment discharge:

$$Q_w^+ \sim b^+, d^+, L^+, S^-$$

$$Q_w^- \sim b^-, d^-, L^-, S^+$$

$$Q_s^+ \sim b^+, d^-, L^+, S^+, P^-$$

$$Q_s- \sim b^-, d^+, L^-, S^-, P^+$$

Combining the four equations above yields additional predictive relationships for concurrent increases or decreases in streamflow and/or sediment discharge:

$$Q_w^+Q_s^+ \sim b^+, d^{+/-}, L^+, S^{+/-}, P^-$$

$$Q_w^-Q_s^- \sim b\text{-}, d^{+/-}, L^-, S^{+/-}, P^+$$

$$Q_w^+Q_s^- \sim b^{+/-}, d^+, L^{+/-}, S^-, P^+$$

$$Q_w^-Q_s^+ \sim b^{+/-}, d^-, L^{+/-}, S^+, P^-$$

Channel Slope

Channel slope, a stream's longitudinal profile, is measured as the difference in elevation between two points in the stream divided by the stream length between the two points. Slope is one of the most critical pieces of design information required when channel

FAST FORWARD

*See **Section E** for a further discussion of dynamic equilibrium.*

modifications are considered. Channel slope directly impacts flow velocity, stream competence, and stream power. Since these attributes drive the geomorphic processes of erosion, sediment transport, and sediment deposition, channel slope becomes a controlling factor in channel shape and pattern.

Most longitudinal profiles of streams are concave upward. As described previously in the discussion of dynamic equilibrium, streams adjust their profile and pattern to try to minimize the time rate of expenditure of potential energy, or stream power, present in flowing water. The concave upward shape of a stream's profile appears to be due to adjustments a river makes to help minimize stream power in a downstream direction. Yang (1983) applied the theory of minimum stream power to explain why most longitudinal streambed profiles are concave upward. In order to satisfy the theory of minimum stream power, which is a special case of the general theory of minimum energy dissipation rate (Yang and Song 1979), the following equation must be satisfied:

$$\frac{dP}{dx} = \gamma \quad Q\frac{dS}{dx} + S\frac{dQ}{dx} \quad = 0$$

Where:

P = QS = Stream power
x = Longitudinal distance
Q = Water discharge
S = Water surface or energy slope
γ = Specific weight of water

Stream power has been defined as the product of discharge and slope. Since stream discharge typically increases in a downstream direction, slope must decrease in order to minimize stream power. The decrease in slope in a downstream direction results in the concave-up longitudinal profile.

Sinuosity is not a profile feature, but it does affect stream slope. Sinuosity is the stream length between two points on a stream divided by the valley length between the two points. For example, if a stream is 2,200 feet long from point A to point B, and if a valley length distance between those two points is 1,000 feet, that stream has a sinuosity of 2.2. A stream can increase its length by increasing its sinuosity, resulting in a decrease in slope. This impact of sinuosity on channel slope must always be considered if channel reconstruction is part of a proposed restoration.

Pools and Riffles

The longitudinal profile is seldom constant, even over a short reach. Differences in geology, vegetation patterns, or human disturbances can result in flatter and steeper reaches within an overall profile. Riffles occur where the stream bottom is higher relative to streambed elevation immediately upstream or downstream. These relatively deeper areas are considered pools. At normal flow, flow velocities decrease in pool areas, allowing fine grained deposition to occur, and increase atop riffles due to the increased bed slope between the riffle crest and the subsequent pool.

Longitudinal Profile Adjustments

A common example of profile adjustment occurs when a dam is constructed on a stream. The typical response to dam construction is channel degradation downstream and aggradation upstream. However, the specific response is quite complex as can be illustrated by considering Lane's relation. Dams typically reduce peak discharges and sediment supply in the downstream reach. According to Lane's relation, a decrease in discharge (Q) should be offset by an increase in slope, yet the decrease in sediment load (Qs) should cause a decrease in slope. This response could be further complicated if armoring occurs (D_{50}^{+}), which would also cause an increase in slope. Impacts are not limited to the main channel, but can include aggradation or degradation on tributaries as well. Aggradation often occurs at the mouths of tributaries downstream of dams (and sometimes in the entire channel) due to the reduction of peak flows on the main stem. Obviously, the ultimate response will be the result of the integration of all these variables.

Channel Cross Sections

Figure 2.16 presents the type of information that should be recorded when collecting stream cross section data. In stable alluvial streams, the high points on each bank represent the top of the bankfull channel.

The importance of the bankfull channel has been established. Channel cross sections need to include enough points to define the channel in relation to a portion of the floodplain on each side. A suggested guide is to include at least one stream width beyond the highest point on each bank for smaller stream corridors and at least enough of the floodplain on larger streams to clearly define its character in relation to the channel.

In meandering streams, the channel cross section should be measured in areas of riffles or crossovers. A riffle or crossover occurs between the apexes of two sequential meanders. The effects of differences in resistance

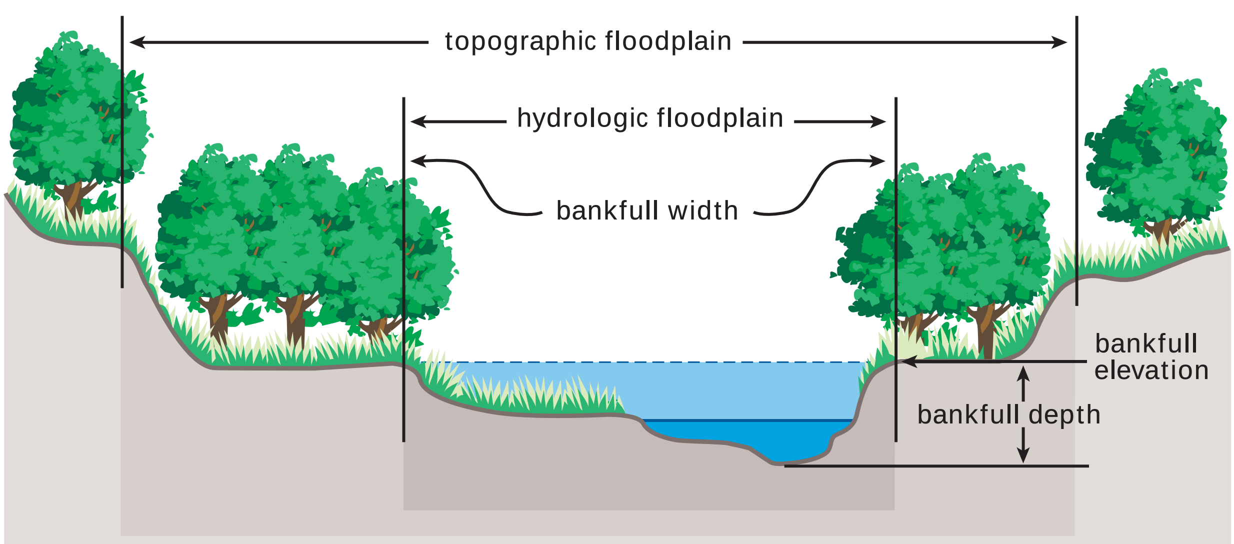


Figure 2.16: Channel cross section.
Information to record when collecting stream cross section data.

to erosion of soil layers are prominent in the outside bends of meanders, and point bars on the insides of the meanders are constantly adjusting to the water and sediment loads being moved by the stream. The stream's cross section changes much more rapidly and frequently in the meander bends. There is more variability in pool cross sections than in riffle cross sections. The cross section in the crossover or riffle area is more uniform .

Resistance to Flow and Velocity

Channel slope is an important factor in determining streamflow velocity. Flow velocity is used to help predict what discharge a cross section can convey. As discharge increases, either flow velocity, flow area, or both must increase.

Roughness plays an important role in streams. It helps determine the depth or stage of flow in a stream reach. As flow velocity slows in a stream reach due to roughness, the depth of flow has to increase to maintain the volume of flow that entered the upstream end of the reach (a concept known as flow continuity). Typical roughness along the boundaries of the stream includes the following:

- Sediment particles of different sizes.
- Bedforms.
- Bank irregularities.
- The type, amount, and distribution of living and dead vegetation.
- Other obstructions.

Roughness generally increases with increasing particle size. The shape and size of instream sediment deposits, or bedforms, also contribute to roughness.

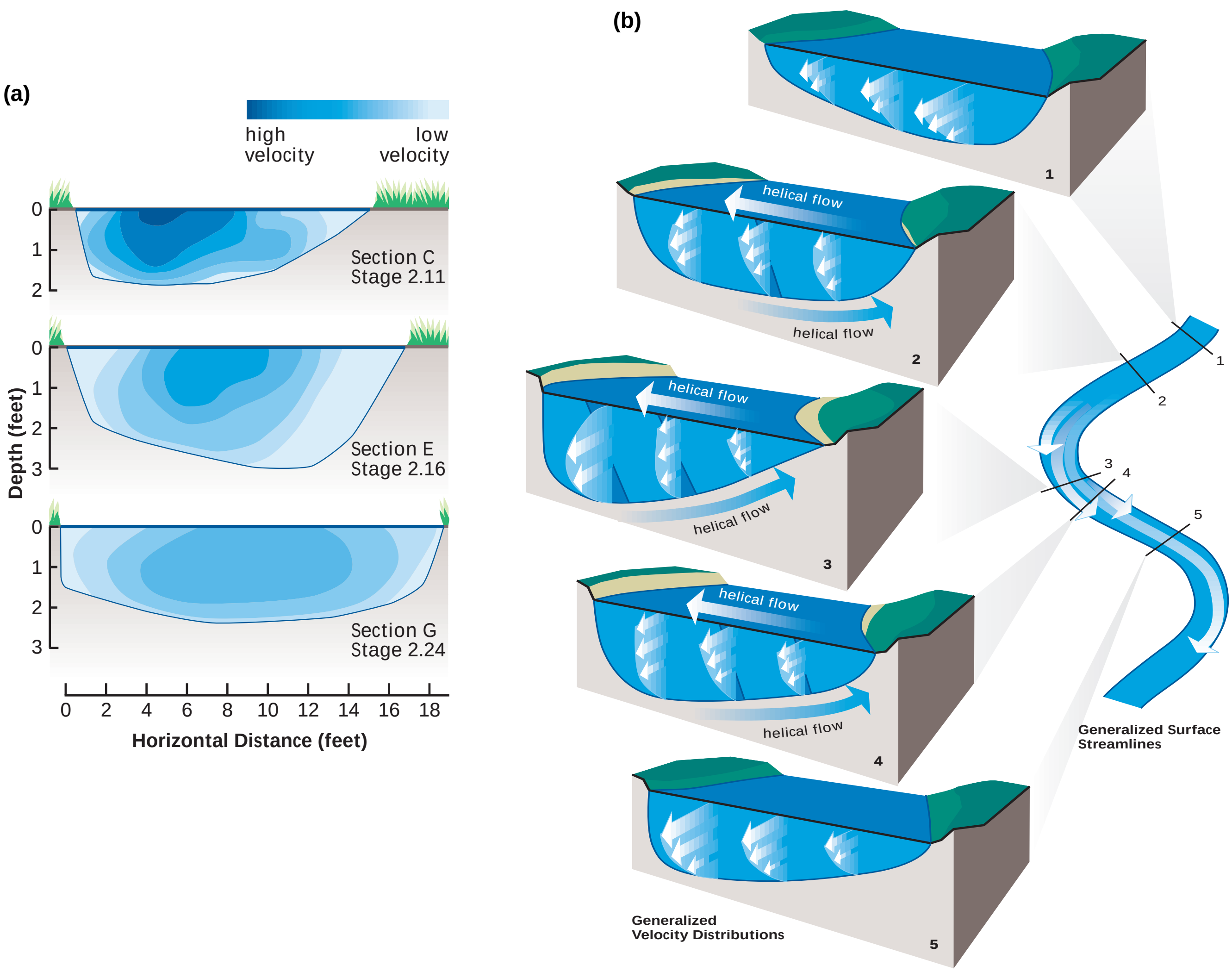
Sand-bottom streams are good examples of how bedform roughness changes with discharge. At very low discharges, the bed of a sand stream may be dominated by ripple bedforms. As flow increases even more, sand dunes may begin to appear on the bed. Each of these bedforms increases the roughness of the stream bottom, which tends to slow velocity.

The depth of flow also increases due to increasing roughness. If discharge continues to increase, a point is reached when the flow velocity mobilizes the sand on the streambed and the entire bed converts again to a planar form. The depth of flow may actually decrease at this point due to the decreased roughness of the bed. If discharge increases further still, antidunes may form. These bedforms create enough friction to again cause the flow depth to increase. The depth of flow for a given discharge in sand-bed streams, therefore, depends on the bedforms present when that discharge occurs.

Vegetation can also contribute to roughness. In streams with boundaries consisting of cohesive soils, vegetation is usually the principal component of roughness. The type and distribution of vegetation in a stream corridor depends on hydrologic and geomorphic processes, but by creating roughness, vegetation can alter these processes and cause changes in a stream's form and pattern.

Meandering streams offer some resistance to flow relative to straight streams. Straight and meandering streams also have different distributions of flow velocity that are affected by the alignment of the stream, as shown in **Figure 2.17**. In straight reaches of a stream, the fastest flow occurs just below the surface near the center of the channel where flow resistance is lowest (see Figure 2.17 (A) Section G). In meanders, velocities are highest at the outside edge due to angular momentum (see Figure 2.17 (B) Section 3). The differences in flow velocity distribution in meandering streams result in both erosion and deposition at the meander bend. Erosion occurs at the outside of bends (cutbanks) from high velocity flows, while the slower velocities at the insides of bends cause deposition on the point bar (which also has been called the *slip-off slope*.

Figure 2.17: Velocity distribution in a (a) straight stream branch and a (b) steam meander.
Stream flow velocities are different through pools and riffles, in straight and curved reaches, across the stream at any point, and at different depths. Velocity distribution also differs dramatically from baseflow conditions through bankfull flows, and flood flows.
Source: Fluvial Processes and Geomorphology, 1964. Published by permission of Dover Publications.



The angular momentum of flow through a meander bend increases the height or *super elevation* at the outside of the bend and sets up a secondary current of flow down the face of the cut bank and across the bottom of the pool toward the inside of the bend. This rotating flow is called *helical flow* and the direction of rotation is illustrated on the diagram on the previous page by the arrows at the top and bottom of cross sections 3 and 4 in the figure.

The distribution of flow velocities in straight and meandering streams is important to understand when planning and designing modifications in stream alignment in a stream corridor restoration. Areas of highest velocities generate the most stream power, so where such velocities intersect the stream boundaries indicates where more durable protection may be needed.

As flow moves through a meander, the bottom water and detritus in the pool are rotated to the surface. This rotation is an important mechanism in moving drifting and benthic organisms past predators in pools. Riffle areas are not as deep as pools, so more turbulent flows occur in these shallow zones. The turbulent flow can increase the dissolved oxygen content of the water and may also increase the oxidation and volatilization of some chemical constituents in water.

Another extremely important function of roughness elements is that they create aquatic habitat. As one example, the deepest flow depths usually occur at the base of cutbanks. These scour holes or pools create very different habitat than occurs in the depositional environment of the slip-off slope.

Active Channels and Floodplains

Floodplains are built by two stream processes, lateral and vertical accretion. Lateral accretion is the deposition of sediment on point bars on the insides of bends of the river. The stream laterally migrates across the floodplain as the outside of the meander bend erodes and the point bar builds with coarse-textured sediment. This naturally occurring process maintains the cross section needed to convey water and sediment from the watershed. Vertical accretion is the deposition of sediment on flooded surfaces. This sediment generally is finer textured than point bar sediments and is considered to be an overbank deposit. Vertical accretion occurs on top of the lateral accretion deposits in the point bars; however, lateral accretion is the dominant process. It typically makes up 60 to 80 percent of the total sediment deposits in floodplains (Leopold et al. 1964). It is apparent that lateral migration of meanders is an important natural process since it plays a critical role in reshaping floodplains.

2.C Physical and Chemical Characteristics

The quality of water in the stream corridor might be a primary objective of restoration, either to improve it to a desired condition or to sustain it. Establishing an appropriate flow regime and geomorphology in a stream corridor may do little to ensure a healthy ecosystem if the physical and chemical characteristics of the water are inappropriate. For example, a stream containing high concentrations of toxic materials or in which high temperatures, low dissolved oxygen, or other physical/chemical characteristics are inappropriate cannot support a healthy stream corridor. Conversely, poor condition of the stream corridor—such as lack of riparian shading, poor controls on erosion, or excessive sources of nutrients and oxygen-demanding waste—can result in degradation of the physical and chemical conditions within the stream.

This section briefly surveys some of the key physical and chemical characteristics of flowing waters. Stream water quality is a broad topic on which many books have been written. The focus here is on a few key concepts that are relevant to stream corridor restoration. The reader is referred to other sources (e.g., Thomann and Mueller 1987, Mills et al. 1985) for a more detailed treatment.

As in the previous sections, the physical and chemical characteristics of streams are examined in both the lateral and longitudinal perspectives. The lateral perspective refers to the influence of the watershed on water quality, with particular attention to riparian areas. The longitudinal perspective refers to processes that affect water quality during transport instream.

Physical Characteristics

Sediment

Section 2.B discussed total sediment loads in the context of the evolution of stream form and geomorphology. In addition to its role in shaping stream form, suspended sediment plays an important role in water quality, both in the water column and at the sediment-water interface. In a water quality context, sediment usually refers to soil particles that enter the water column from eroding land. Sediment consists of particles of all sizes, including fine clay particles, silt, and gravel. The term sedimentation is used to describe the deposition of sediment particles in waterbodies.

Although sediment and its transport occur naturally in any stream, changes in sediment load and particle size can have negative impacts (**Figure 2.18**). Fine sediment can severely alter aquatic communities. Sediment may clog and abrade fish gills, suffocate eggs and aquatic insect larvae on the bottom, and fill in the pore space between bottom cobbles where fish lay eggs. Sediment interferes with recreational activities and aesthetic enjoyment at waterbodies by reducing water clarity and filling in waterbodies.

Figure 2.18: Stream sedimentation. *Although sediment and its transport occur naturally, changes in sediment load and particle size have negative impacts.*

Sediment also may carry other pollutants into waterbodies. Nutrients and toxic chemicals may attach to sediment particles on land and ride the particles into surface waters where the pollutants may settle with the sediment or become soluble in the water column.

Studies have shown that fine sediment intrusion can significantly impact the quality of spawning habitat (Cooper 1965, Chapman 1988). Fine sediment intrusion into streambed gravels can reduce permeability and intragravel water velocities, thereby restricting the supply of oxygenated water to developing salmonid embryos and the removal of their metabolic wastes. Excessive fine sediment deposition can effectively smother incubating eggs and entomb alevins and fry. A sediment intrusion model (Alonso et al. 1996) has been developed, verified, and validated to predict the within-redd (spawning area) sediment accumulation and dissolved oxygen status.

Sediment Across the Stream Corridor

Rain erodes and washes soil particles off plowed fields, construction sites, logging sites, urban areas, and strip-mined lands into waterbodies. Eroding streambanks also deposit sediment into waterbodies. In sum, sediment quality in the stream represents the net result of erosion processes in the watershed.

The lateral view of sediment is discussed in more detail in Section 2.B. It is worth noting, however, that from a water quality perspective, interest may focus on specific fractions of the sediment load. For instance, controlling fine sediment load is often of particular concern for restoration of habitat for salmonid fish.

Restoration efforts may be useful for controlling loads of sediment and sediment-associated pollutants from the watershed to streams. These may range from efforts to reduce upland erosion to treatments that reduce sediment delivery through the riparian zone. Design of restoration treatments is covered in detail in Chapter 8.

Sediment Along the Stream Corridor

The longitudinal processes affecting sediment transport from a water quality perspective are the same as those discussed from a geomorphic perspective in Section 2.B. As in the lateral perspective, interest from a water quality point of view may be focused on specific sediment size fractions, particularly the fine sediment fraction, because of its effect on water quality, water temperature, habitat, and biota.

Water Temperature

Water temperature is a crucial factor in stream corridor restoration for a number of reasons. First, dissolved oxygen solubility decreases with increasing water temperature, so the stress imposed by oxygen-demanding waste increases with higher temperatures. Second, temperature governs many biochemical and physiological processes in cold-blooded aquatic organisms, and increased temperatures can increase metabolic and reproductive rates throughout the food chain. Third, many aquatic species can tolerate only a limited range of temperatures, and shifting the maximum and minimum temperatures within a stream can have profound effects on species composition. Finally, temperature also affects many abiotic chemical processes, such as reaeration rate, sorption of organic chemicals to particulate matter, and volatilization rates. Temperature increases can lead to increased stress from toxic compounds, for which the dissolved fraction is usually the most bioactive fraction.

Water Temperature Across the Stream Corridor

Water temperature within a stream reach is affected by the temperature of water upstream, processes within the stream reach, and the temperature of influent water. The lateral view addresses the effects of the temperature of influent water.

The most important factor for temperature of influent water within a stream reach is the balance between water arriving via surface and ground water pathways. Water that flows over the land surface to a stream has the opportunity to gain heat through contact with surfaces heated by the sun. In contrast, ground water is usually cooler in summer and tends to reflect average annual temperatures in the watershed. Water flow via shallow ground water pathways may lie between the average annual temperature and ambient temperatures during runoff events.

Both the fraction of runoff arriving via surface pathways and the temperature of surface runoff are strongly affected by the amount of impervious surfaces within a watershed. For example, hot paved surfaces in a watershed can heat surface runoff and significantly increase the temperature of streams that receive the runoff.

☞

FAST FORWARD

*See **Section D** for more detail on the effect of cover on water temperature.*

Water Temperature Along the Stream Corridor

Water also is subject to thermal loading through direct effects of sunlight on streams. For the purposes of restoration, land use practices that remove overhead cover or that decrease baseflows can increase instream temperatures to levels that exceed critical thermal maxima for fishes (Feminella and Matthews 1984). Maintaining or restoring normal temperature ranges can therefore be an important goal for restoration.

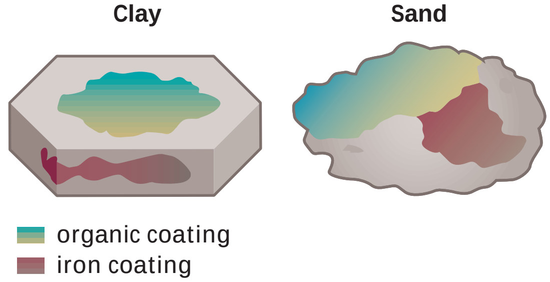
Chemical Constituents

Previous chapters have discussed the physical journey of water as it moves through the hydrologic cycle. Rain percolates to the ground water table or becomes overland flow, streams collect this water and route it toward the ocean, and evapotranspiration occurs throughout the cycle. As water makes this journey, its chemistry changes. While in the air, water equilibrates with atmospheric gases. In shallow soils, it undergoes chemical exchanges with inorganic and organic matter and with soil gases. In ground water, where transit times are longer, there are more opportunities for minerals to dissolve. Similar chemical reactions continue along stream corridors. Everywhere, water interacts with everything it touches—air, rocks, bacteria, plants, and fish—and is affected by human disturbances.

Scientists have been able to define several interdependent cycles for many of the common dissolved constituents in water. Central among these cycles is the behavior of oxygen, carbon, and nutrients, such as nitrogen (N), phosphorus (P), sulfur (S), and smaller amounts of common trace elements.

Iron, for example, is an essential element in the metabolism of animals and plants. Iron in aquatic systems may be present in one of two oxidation states. Ferric iron (Fe^{3+}) is the more oxidized form and is very sparingly soluble in water. The reduced form, ferrous iron (Fe^{2+}), is more soluble by many orders of magnitude. In many aquatic systems, such as lakes for example, iron can cycle from the ferric state to the ferrous state and back again (**Figure 2.19**). The oxidation of ferrous iron followed by the precipitation of ferric iron results in iron coatings on the surfaces of some stream sediments. These coatings, along with organic coatings, play a substantial role in the aquatic chemistry of toxic trace elements and toxic organic chemicals. The chemistry of toxic organic chemicals and metals, along with the cycling and chemistry of oxygen, nitrogen, and phosphorus, will be covered later in this section.

Figure 2.19: The organic coatings on suspended sediment from streams.
Water chemistry determines whether sediment will carry adsorbed materials or if stream sediments will be coated.



The total concentration of all dissolved ions in water, also known as salinity, varies widely. Precipitation typically contains only a few parts per thousand (ppt) of dissolved solids, while the salinity of seawater averages about 35 ppt (**Table 2.5**). The concentration of dissolved solids in freshwater may vary from only 10 to 20 mg/L in a pristine mountain stream to several hundred mg/L in many rivers. Concentrations may exceed 1,000 mg/L in arid watersheds. A dissolved solids concentration of less than 500 mg/L is recommended for public drinking water, but this threshold is exceeded in many areas of the country. Some crops (notably fruit trees and beans) are sensitive to even modest salinity, while other crops, such as cotton, barley, and beets, tolerate high concentrations of dissolved solids. Agricultural return water from irrigation may increase salinity in streams, particularly in the west. Recommended salinity limits for livestock vary from 2,860 mg/L for poultry to 12,900 mg/L for adult sheep. Plants, fish, and other aquatic life also vary widely in their adaptation to different concentrations of dissolved solids. Most species have a maximum salinity tolerance, and few can live in very pure water of very low ionic concentration.

pH, Alkalinity, and Acidity

Alkalinity, acidity, and buffering capacity are important characteristics of water that affect its suitability for biota and influence chemical reactions. The acidic or basic (alkaline) nature of water is commonly quantified by the negative logarithm of the hydrogen ion concentration, or pH. A pH value of 7 represents a neutral condition; a pH value less than 5 indicates moderately acidic conditions; a pH value greater than 9 indicates moderately alkaline conditions. Many biological processes, such as reproduction, cannot function in acidic or alkaline waters. In particular, aquatic organisms may suffer an osmotic imbalance under sustained exposure to low pH waters. Rapid fluctuations in pH also can stress aquatic organisms. Finally, acidic conditions also can aggravate toxic contamination problems through increased solubility, leading to the release of toxic chemicals stored in stream sediments.

	Samples					
Constituent	1	2	3	4	5	6
SiO_2	0.0		1.2	0.3		0.1
Al	.01					
Fe	.00					.015
Ca	.0	.65	1.2	.8	1.41	.075
Mg	.2	.14	.7	1.2		.027
Na	.6	.56	.0	9.4	.42	.220
K	.6	.11	.0	.0		.072
NH_4	.0					
HCO_3	3		7	4		
SO_4	1.6	2.18	.7	7.6	2.14	1.1
Cl	.2	.57	.8	17	.22	
NO_2	.02		.00	.02		
NO_3	.1	.62	.2	.0		
Total dissolved solids	4.8		8.2	38		
pH	5.6		6.4	5.5		4.9

1. Snow, Spooner Summit. U.S. Highway 50, Nevada (east of Lake Tahoe) (Feth, Rogers, and Roberson, 1964).
2. Average composition of rain, August 1962 to July 1963, at 27 points in North Carolina and Virginia (Gambell and Fisher, 1966).
3. Rain, Menlo Park, Calif., 7:00 p.m. Jan. 9 to 8:00 a.m. Jan 10, 1958 (Whitehead and Feth, 1964).
4. Rain, Menlo Park, Calif., 8:00 a.m. to 2:00 p.m. Jan 10, 1958 (Whitehead and Feth, 1964).
5. Average for inland sampling stations in the United States for 1 year. Data from Junge and Werby (1958), as reported by Whitehead and Feth (1964).
6. Average composition of precipitation, Williamson Creek, Snohomish County, Wash., 1973-75. Also reported: As, 0.00045 mg/L; Cu 0.0025 mg/L; Pb, 0.0033 mg/L; Zn, 0.0036 mg/L (Deithier, D.P., 1977, Ph.D. thesis. University of Washington, Seattle).

Table 2.5: Composition, in milligrams per liter, of rain and snow.

pH, Alkalinity, and Acidity Across the Stream Corridor

The pH of runoff reflects the chemical characteristics of precipitation and the land surface. Except in areas with significant ocean spray, the dominant ion in most precipitation is bicarbonate (HCO_3^-). The bicarbonate ion is produced by carbon dioxide reacting with water:

$$H_2O + CO_2 = H^+ + HCO_3^-$$

This reaction also produces a hydrogen ion (H^+), thus increasing the hydrogen ion concentration and acidity and lowering the pH. Because of the presence of CO_2 in the atmosphere, most rain is naturally slightly acidic, with a pH of about 5.6. Increased acidity in rainfall can be caused by inputs, particularly from burning fossil fuels.

As water moves through soils and rocks, its pH may increase or decrease as additional chemical reactions occur. The carbonate buffering system controls the acidity of most waters. Carbonate buffering results from chemical equilibrium between calcium, carbonate, bicarbonate, carbon dioxide, and hydrogen ions in the water and carbon dioxide in the atmosphere. Buffering causes waters to resist changes in pH (Wetzel 1975). Alkalinity refers to the acid-neutralizing capacity of water and usually refers to those compounds that shift the pH in an alkaline direction (APHA 1995, Wetzel 1975). The amount of buffering is related to the alkalinity and primarily determined by carbonate and bicarbonate concentration, which are introduced into the water from dissolved calcium carbonate (i.e., limestone) and similar minerals present in the watershed. For example, when water interacts with limestone, the following dissolution reaction occurs:

$$H^+ + CaCO_3 = Ca^{2+} + HCO_3^-$$

This reaction consumes hydrogen ions, thus raising the pH of the water. Conversely, runoff may acidify when all alkalinity in the water is consumed by acids, a process often attributed to the input of strong mineral acids, such as sulfuric acid, from acid mine drainage, and weak organic acids, such as humic and fulvic acids, which are naturally produced in large quantities in some types of soils, such as those associated with coniferous forests, bogs, and wetlands. In some streams, pH levels can be increased by restoring degraded wetlands that intercept acid inputs, such as acid mine drainage, and help neutralize acidity by converting sulfates from sulfuric acid to insoluble nonacidic metal sulfides that remain trapped in wetland sediments.

pH, Alkalinity, Acidity Along the Stream Corridor

Within a stream, similar reactions occur between acids in the water, atmospheric CO_2, alkalinity in the water column, and streambed material. An additional characteristic of pH in some poorly buffered waters is high daily variability in pH levels attributable to biological processes that affect the carbonate buffering system. In waters with large standing crops of aquatic plants, uptake of carbon dioxide by plants during photosynthesis removes carbonic acid from the water, which can increase pH by several units. Conversely, pH levels may fall by several units during the night when photosynthesis does not occur and plants give off carbon dioxide. Restoration techniques that decrease instream plant growth through increased shading or reduction in nutrient loads or that increase reaeration also tend to stabilize highly variable pH levels attributable to high rates of photosynthesis.

The pH within streams can have important consequences for toxic materials. High acidity or high alkalinity tend to convert insoluble metal sulfides to soluble forms and can increase the concentration of toxic metals. Conversely, high pH can promote ammonia toxicity. Ammonia is present in water in two forms, unionized (NH_3) and ionized (NH_4^+). Of these two forms of ammonia, un-ionized ammonia is relatively highly toxic to aquatic life, while ionized ammonia is relatively negligibly toxic. The proportion of un-ionized ammonia is determined by the pH and temperature of the water (Bowie et al. 1985)—as pH or temperature increases, the proportion of un-ionized ammonia and the toxicity also increase. For example, with a pH of 7 and a temperature of 68 °F, only about 0.4 percent of the total ammonia is in the un-ionized form, while at a pH of 8.5 and a temperature of 78 °F, 15 percent of the total ammonia is in the un-ionized form, representing 35 times greater potential toxicity to aquatic life.

Dissolved Oxygen

Dissolved oxygen (DO) is a basic requirement for a healthy aquatic ecosystem. Most fish and aquatic insects “breathe” oxygen dissolved in the water column. Some fish and aquatic organisms, such as carp and sludge worms, are adapted to low oxygen conditions, but most sport fish species, such as trout and salmon, suffer if DO concentrations fall below a concentration of 3 to 4 mg/l. Larvae and juvenile fish are more sensitive and require even higher concentrations of DO (USEPA 1997).

Many fish and other aquatic organisms can recover from short periods of low DO in the water. However, prolonged episodes of depressed dissolved oxygen concentrations of 2 mg/l or less can result in “dead” waterbodies. Prolonged exposure to low DO conditions can suffocate adult fish or reduce their reproductive survival by suffocating sensitive eggs and larvae, or can starve fish by killing aquatic insect larvae and other prey. Low DO concentrations also favor anaerobic bacteria that produce the noxious gases or foul odors often associated with polluted waterbodies.

Water absorbs oxygen directly from the atmosphere, and from plants as a result of photosynthesis. The ability of water to hold oxygen is influenced by temperature and salinity. Water loses oxygen primarily by respiration of aquatic plants, animals, and microorganisms. Due to their shallow depth, large surface exposure to air, and constant motion, undisturbed streams generally contain an abundant DO supply. However, external loads of oxygen-demanding wastes or excessive plant growth induced by nutrient loading followed by death and decomposition of vegetative material can deplete oxygen.

FAST FORWARD

*See **Section D** for more information on DO.*

Dissolved Oxygen Across the Stream Corridor

Oxygen concentrations in the water column fluctuate under natural conditions, but oxygen can be severely depleted as a result of human activities that introduce large quantities of biodegradable organic materials into surface waters. Excess loading of nutrients also can deplete oxygen when plants within a stream produce large quantities of plant biomass.

Loads of oxygen-demanding waste usually are reported as *biochemical oxygen demand (BOD)*. BOD is a measure of the amount of oxygen required to oxidize organic material in water by biological activity. As such, BOD is an equivalent indicator rather than a true physical or chemical substance. It measures the total concentration of DO that eventually would be demanded as wastewater degrades in a stream.

BOD also is often separated into carbonaceous and nitrogenous components. This is because the two fractions tend to degrade at different rates. Many water quality models for dissolved oxygen require as input estimates of ultimate carbonaceous BOD

($CBOD_u$) and either ultimate nitrogenous BOD ($NBOD_u$) or concentrations of individual nitrogen species.

Oxygen-demanding wastes can be loaded to streams by point source discharges, nonpoint loading, and ground water. BOD loads from major point sources typically are controlled and monitored and thus are relatively easy to analyze. Nonpoint source loads of BOD are much more difficult to analyze. In general, any loading of organic material from a watershed to a stream results in an oxygen demand. Excess loads of organic material may arise from a variety of land use practices, coupled with storm events, erosion, and washoff. Some agricultural activities, particularly large-scale animal operations and improper manure application, can result in significant BOD loads. Land-disturbing activities of silviculture and construction can result in high organic loads through the erosion of organic topsoil. Finally, urban runoff often is loaded with high concentrations of organic materials derived from a variety of sources.

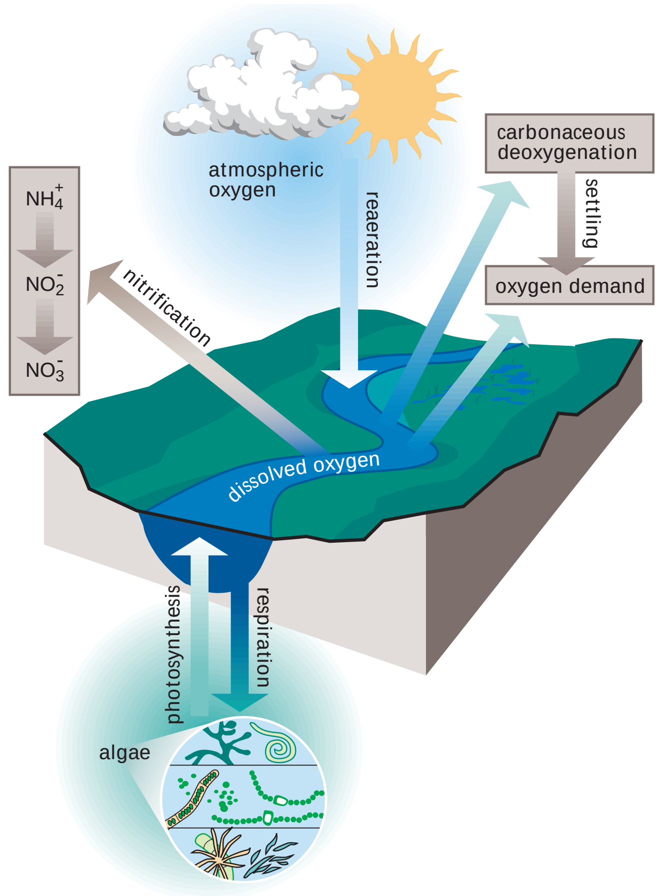


Figure 2.20: Interrelationship of major kinetic processes for BOD and DO as represented by water quality models. *Complex, interacting physical and chemical processes can sometimes be simplified by models in order to plan a restoration.*

Dissolved Oxygen Along the Stream Corridor

Within a stream, DO content is affected by reaeration from the atmosphere, production of DO by aquatic plants as a by-product of photosynthesis, and consumption of DO in respiration by plants, animals, and, most importantly, microorganisms.

Major processes affecting the DO balance within a stream are summarized in **Figure 2.20**. This includes the following components:

- Carbonaceous deoxygenation
- Nitrogenous deoxygenation (nitrification)
- Reaeration
- Sediment oxygen demand
- Photosynthesis and respiration of plants.

Reaeration is the primary route for introducing oxygen into most waters. Oxygen gas (O_2) constitutes about 21 percent of the atmosphere and readily dissolves in water. The saturation concentration of DO in water is a measure of the maximum amount of oxygen that water can hold at a given temperature. When oxygen exceeds the saturation concentration, it tends to degas to the atmosphere. When oxygen is below the saturation concentration, it tends to diffuse from the atmosphere to water. The saturation concentration of oxygen decreases with temperature according to a complex power function equation (APHA 1995). In addition to temperature, the saturation concentration is affected by water salinity and the atmospheric pressure. As the salinity of water increases, the saturation concentration decreases. As the atmospheric pressure increases the saturation concentration also increases.

Interactions between atmospheric and DO are driven by the partial pressure gradient in the gas phase and the concentration gradient in the liquid phase (Thomann and Mueller 1987). Turbulence and mixing in either phase decrease these gradients and increase reaeration, while a quiescent, stagnant surface or films on the surface reduce reaeration. In general, oxygen transfer in natural waters depends on the following:

- Internal mixing and turbulence due to velocity gradients and fluctuation
- Temperature
- Wind mixing
- Waterfalls, dams, and rapids
- Surface films
- Water column depth.

Stream restoration techniques often take advantage of these relationships, for instance by the installation of artificial cascades to increase reaeration. Many empirical formulations have been developed for estimating stream reaeration rate coefficients; a detailed summary is provided in Bowie et al. (1985).

In addition to reaeration, oxygen is produced instream by aquatic plants. Through photosynthesis, plants capture energy from the sun to fix carbon dioxide into reduced organic matter:

$$6\ CO_2 + 6\ H_2O = C_6H_{12}O_6 + 6\ O_2$$

Note that photosynthesis also produces oxygen. Plants utilize their simple photosynthetic sugars and other nutrients (notably nitrogen [N], phosphorus [P,] and sulfur [S] with smaller amounts of several common and trace elements) to operate their metabolism and to build their structures.

Most animal life depends on the release of energy stored by plants in the photosynthetic process. In a reaction that is the reverse of photosynthesis, animals consume plant material or other animals and oxidize the sugars, starches, and proteins to fuel their metabolism and build their own structure. This process is known as respiration and consumes dissolved oxygen. The actual process of respiration involves a series of energy converting oxidation-reduction reactions. Higher animals and many microorganisms depend on sufficient dissolved oxygen as the terminal electron acceptor in these reactions and cannot survive without it. Some microorganisms are able to use other compounds (such as nitrate and sulfate) as electron acceptors in metabolism and can survive in anaerobic (oxygen-depleted) environments.

Detailed information on analysis and modeling of DO and BOD in streams is contained in a number of references (e.g., Thomann and Mueller 1987), and a variety of well-tested computer models are available. Most stream water quality models account for CBOD in the water column separately from NBOD (which is usually represented via a direct mass balance of nitrogen species) and *sediment oxygen demand* or *SOD*. SOD represents the oxygen demand of sediment organism respiration and the benthic decomposition of organic material. The demand of oxygen by sediment and benthic organisms can, in some instances, be a significant fraction of the total oxygen demand in a stream. This is particularly true in small streams. The effects may be particularly acute during low-flow and high-temperature conditions, as microbial activity tends to increase with increased temperature.

The presence of toxic pollutants in the water column can indirectly lower oxygen concentrations by killing algae, aquatic weeds, or fish, which provide an abundance of food for oxygen-consuming bacteria. Oxygen depletion also can result from chemical reactions that do not involve bacteria. Some pollutants trigger chemical reactions that place a chemical oxygen demand on receiving waters.

Nutrients

In addition to carbon dioxide and water, aquatic plants (both algae and higher plants) require a variety of other elements to support their bodily structures and metabolism. Just as with terrestrial plants, the most important of these elements are nitrogen and phosphorus. Additional nutrients, such as potassium, iron, selenium, and silica, are needed in smaller amounts and generally are not limiting factors to plant growth. When these chemicals are limited, plant growth may be limited. This is an important consideration in stream management. Plant biomass (either created instream or loaded from the watershed) is necessary to support the food chain. However, excessive growth of algae and other aquatic plants instream can result in nuisance conditions, and the depletion of dissolved oxygen during nonphotosynthetic periods by the respiration of plants and decay of dead plant material can create conditions unfavorable to aquatic life.

Phosphorus in freshwater systems exists in either a particulate phase or a dissolved phase. Both phases include organic and inorganic fractions. The organic particulate phase includes living and dead particulate matter, such as plankton and detritus. Inorganic particulate phosphorus includes phosphorus precipitates and phosphorus adsorbed to particulates. Dissolved organic phosphorus includes organic phosphorus excreted by organisms and colloidal phosphorus compounds. The soluble inorganic phosphate forms $H_2PO_4^-$, HPO_4^{2-}, and PO_4^{3-}, collectively known as *soluble reactive phosphorus (SRP)* are readily available to plants. Some condensed phosphate forms, such as those found in detergents, are inorganic but are not directly available for plant uptake. Aquatic plants require nitrogen and phosphorus in different amounts. For phytoplankton, as an example, cells contain approximately 0.5 to 2.0 µg phosphorus per µg chlorophyll, and 7 to 10 µg nitrogen per µg chlorophyll. From this relationship, it is clear that the ratio of nitrogen and phosphorus required is in the range of 5 to 20 (depending on the characteristics of individual species) to support full utilization of available nutrients and maximize plant growth.

When the ratio deviates from this range, plants cannot use the nutrient present in excess amounts. The other nutrient is then said to be the limiting nutrient on plant growth. In streams experiencing excessive nutrient loading, resource managers often seek to control loading of the limiting nutrient at levels that prevent nuisance conditions.

In the aquatic environment, nitrogen can exist in several forms—dissolved nitrogen gas (N_2), ammonia and ammonium ion (NH_3 and NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), and organic nitrogen as proteinaceous matter or in dissolved or particulate phases. The most important forms of nitrogen in terms of their immediate impacts on water quality are the readily available ammonia ions, nitrites, and nitrates. Because they must be converted to a form more usable by plants, particulate and organic nitrogen are less important in the short term.

It may seem unusual that nitrogen could limit plant growth, given that the atmosphere is about 79 percent nitrogen gas. However, only a few lifeforms (for example, certain bacteria and blue-green algae) have the ability to fix nitrogen gas from the atmosphere. Most plants can use nitrogen only if it is available as ammonia (NH_3, commonly present in water as the ionic form ammonium, NH_4^+) or as nitrate (NO_3^-) (**Figure 2.21**). However, in freshwater systems, growth of aquatic plants is more commonly limited by phosphorus than by nitrogen. This limitation occurs because

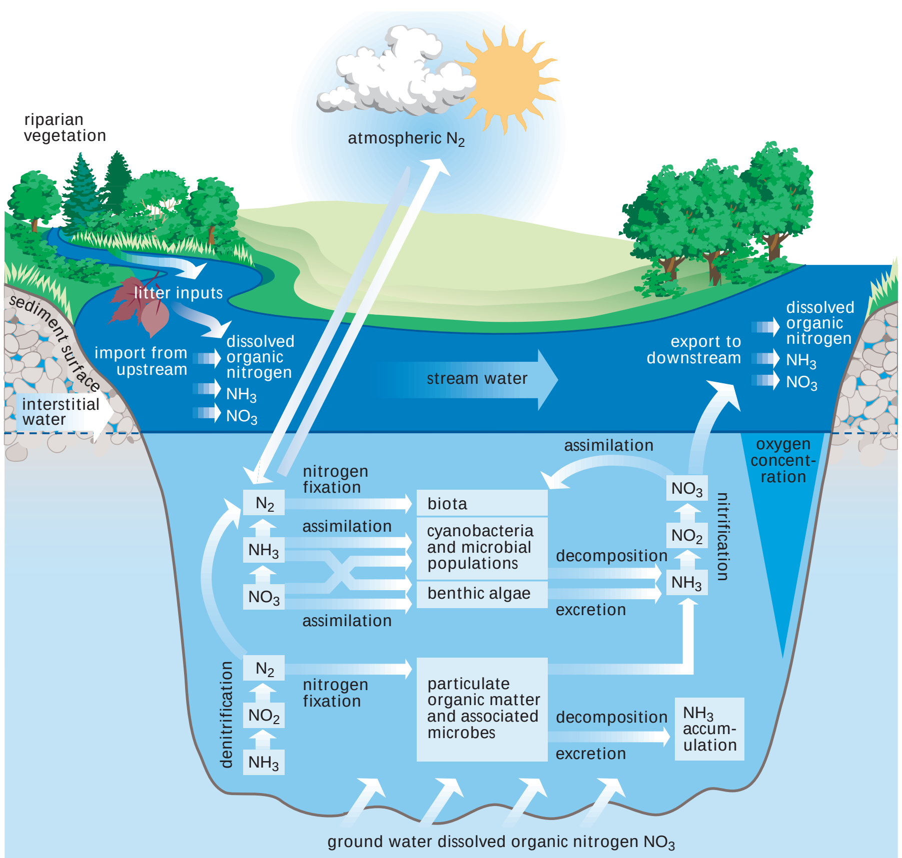


Figure 2.21: Dynamics and transformations of nitrogen in a stream ecosystem.
Nutrient cycling from one form to another occurs with changes in nutrient inputs, as well as temperature and oxygen available.

phosphate (PO_4^{3-}) forms insoluble complexes with common constituents in water (Ca^{++} and variable amounts of OH^-, Cl^-, and F^-). Phosphorus also sorbs to iron coatings on clay and other sediment surfaces and is therefore removed from the water column by chemical processes, resulting in the reduced ability of the water body to support plant growth.

Nutrients Across the Stream Corridor

Both nitrogen and phosphorus are delivered to surface waters at an elevated rate as a result of human activities, including point source discharges of treated wastewater and nonpoint sources, such as agriculture and urban development. In many developed watersheds, a major source of nutrients is the direct discharge of treated waste from wastewater treatment plants, as well as combined sewer overflows (CSOs). Such point source discharges are regulated under the National Pollutant Discharge Elimination System (NPDES) and usually are well characterized by monitoring. The NPDES requires permitted dischargers to meet both numeric and narrative water quality standards in streams. While most states do not have numeric standards for nutrients, point source discharges of nutrients are recognized as a factor leading to stream degradation and failure to achieve narrative water quality standards. As a result, increasingly stringent limitations on nutrient concentrations in wastewater treatment plant effluent (particularly phosphorus) have been imposed in many areas.

In many cases the NPDES program has significantly cleaned up rivers and streams; however, many streams still do not meet water quality standards, even with increasingly stringent regulatory standards. Scientists and regulators now understand that the dominant source of nutrients in many streams is from nonpoint sources within the stream's watershed, not from point sources such as wastewater treatment plants. Typical land uses that contribute to the nonpoint contamination of streams are the application of fertilizers to agricultural fields and suburban lawns, the improper handling of animal wastes from livestock operations), and the disposal of human waste in septic systems. Storm runoff from agricultural fields can contribute nutrients to a stream in dissolved forms as well as particulate forms.

Because of its tendency to sorb to sediment particles and organic matter, phosphorus is transported primarily in surface runoff with eroded sediments. Inorganic nitrogen, on the other hand, does not sorb strongly and can be transported in both particulate and dissolved phases in surface runoff. Dissolved inorganic nitrogen also can be transported through the unsaturated zone (interflow) and ground water to waterbodies. **Table 2.6** presents common point and nonpoint sources of nitrogen and phosphorus loading and shows the approximate concentrations delivered. Note that nitrates are naturally occurring in some soils.

Table 2.6: Sources and concentrations of pollutants from common point and nonpoint sources.

Source	Total Nitrogen (mg/L)	Total Phosphorus (mg/L)
Urban runoff[a]	3-10	0.2-1.7
Livestock operations[a]	6-800[b]	4-5
Atmosphere (wet deposition)[a]	0.9	0.015[c]
90% forest[d]	0.06-0.19	0.006-0.012
50% forest[d]	0.18-0.34	0.013-0.015
90% agriculture[d]	0.77-5.04	0.085-0.104
Untreated wastewater[a]	35	10
Treated wastewater[a,e]	30	10

[a] Novotny and Olem (1994).
[b] As organic nitrogen.
[c] Sorbed to airborne particulate.
[d] Omernik (1977).
[e] With secondary treatment.

Nutrients Along the Stream Corridor

Nitrogen, because it does not sorb strongly to sediment, moves easily between the substrate and the water column and cycles continuously. Aquatic organisms incorporate dissolved and particulate inorganic nitrogen into proteinaceous matter. Dead organisms decompose and nitrogen is released as ammonia ions and then converted to nitrite and nitrate, where the process begins again.

Phosphorus undergoes continuous transformations in a freshwater environment. Some phosphorus will sorb to sediments in the water column or substrate and be removed from circulation. The SRP (usually as orthophosphate) is assimilated by aquatic plants and converted to organic phosphorus. Aquatic plants then may be consumed by detritivores and grazers, which in turn excrete some of the organic phosphorus as SRP. Continuing the cycle, the SRP is rapidly assimilated by aquatic plants.

Toxic Organic Chemicals

Pollutants that cause toxicity in animals or humans are of obvious concern to restoration efforts. *Toxic organic chemicals (TOC)* are synthetic compounds that contain carbon, such as polychlorinated biphenyls (PCBs) and most pesticides and herbicides. Many of these synthesized compounds tend to persist and accumulate in the environment because they do not readily break down in natural ecosystems. Some of the most toxic synthetic organics, DDT and PCBs, have been banned from use in the United States for decades yet continue to cause problems in the aquatic ecosystems of many streams.

Toxic Organic Chemicals Across the Stream Corridor

TOCs may reach a water body via both point and nonpoint sources. Because permitted NPDES point sources must meet water quality standards instream and because of whole effluent toxicity requirements, continuing TOC problems in most streams are due to nonpoint loading, recycling of materials stored in stream and riparian sediments, illegal dumping, or accidental spills. Two important sources of nonpoint loading of organic chemicals are application of pesticides and herbicides in connection with agriculture, silviculture, or suburban lawn care, and runoff from potentially polluted urban and industrial land uses.

The movement of organic chemicals from the watershed land surface to a water body is largely determined by the characteristics of the chemical, as discussed below under the longitudinal perspective. Pollutants that tend to sorb strongly to soil particles are primarily transported with eroded sediment. Controlling sediment delivery from source area land uses is therefore an effective management strategy. Organic chemicals with significant solubility may be transported directly with the flow of water, particularly stormflow from impervious urban surfaces.

Toxic Organic Chemicals Along the Stream Corridor

Among all the elements of the earth, carbon is unique in its ability to form a virtually infinite array of stable covalent bonds with itself: long chains, branches and rings, spiral helixes. Carbon molecules can be so complex that they are able to encode information for the organization of other carbon structures and the regulation of chemical reactions.

The chemical industry has exploited this to produce many useful organic chemicals: plastics, paints and dyes, fuels, pesticides, pharmaceuticals, and other items of modern life. These products and their associated wastes and by-products can interfere with the health of aquatic ecosystems. Understanding the transport and fate of *synthetic organic compounds (SOC)* in aquatic environments continues to challenge scientists. Only a general overview of the processes that govern the behavior of these chemicals along stream corridors is presented here.

Solubility

It is the nature of the carbon-carbon bond that electrons are distributed relatively uniformly between the bonded atoms. Thus a chained or ringed hydrocarbon is a fairly nonpolar compound. This nonpolar nature is dissimilar to the molecular structure of water, which is a very polar solvent.

On the general principle that “like dissolves like,” dissolved constituents in water tend to be polar. Witness, for example, the ionic nature of virtually all inorganic constituents discussed thus far in this chapter. How does an organic compound become dissolved in water? There are several ways. The compound can be relatively small, so it minimizes its disturbance of the polar order of things in aqueous solution. Alternatively, the compound may become more polar by adding polar functional groups (**Figure 2.22**). Alcohols are organic compound with -OH groups attached; organic acids are organic compound with attached -COOH groups. These functional groups are highly polar and increase the solubility of any organic compound. Even more solubility in water is gained by ionic functional groups, such as $-COO^-$.

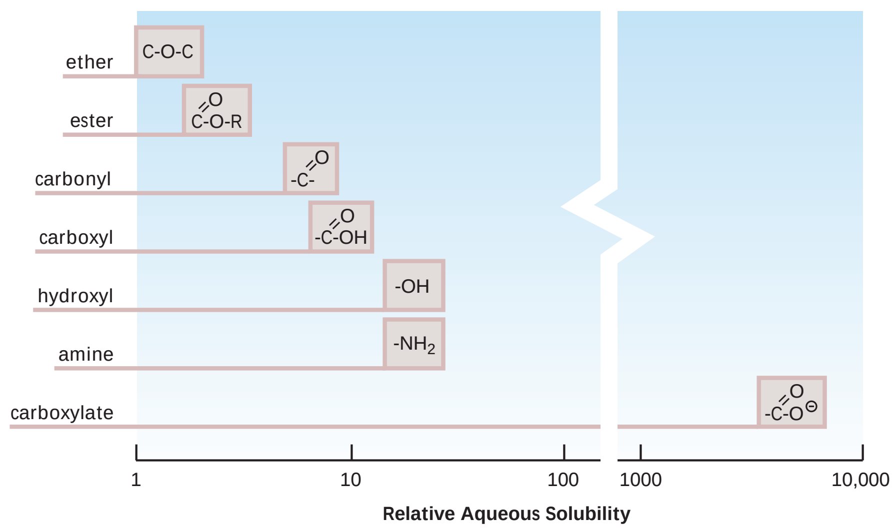


Figure 2.22: Relative aqueous solubility of different functional groups.
The solubility of a contaminant in water largely determines the extent to which it will impact water quality.

Another way that solubility is enhanced is by increased aromaticity. Aromaticity refers to the delocalized bonding structure of a ringed compound like benzene (**Figure 2.23**). (Indeed, all aromatic compounds can be considered derivatives of benzene.) Because electrons are free to “dance around the ring” of the benzene molecule, benzene and its derivatives are more compatible with the polar nature of water.

A simple example will illustrate the factors enhancing aqueous solubility of organic compounds. Six compounds, each having six carbons, are shown in **Table 2.7**. Hexane is a simple hydrocarbon, an alkane whose solubility is 10 mg/L. Simply by adding a single -OH group, which converts hexane to the alcohol hexanol, solubility is increased to 5,900 mg/L. You can bend hexane into a ringed alkane structure called cyclohexane. Forming the ring makes cyclohexane smaller than hexane and increases its solubility, but only to 55 mg/L. Making the ring aromatic by forming the six-carbon benzene molecule increases solubility all the way to 1,780 mg/L. Adding an -OH to benzene to form a phenol leads to another dramatic increase in solubility (to 82,000 mg/L). Adding a chloride atom to the benzene ring diminishes its aromatic character (chloride inhibits the dancing electrons), and thus the solubility of chlorobenzene (448 mg/L) is less than benzene.

Sorption

In the 1940s, a young pharmaceutical industry sought to develop medicines that could be transported in digestive fluids and blood (both of which are essentially aqueous solutions) and

Figure 2.23: Aromatic hydrocarbons.
Benzene is soluble in water because of it's "aromatic" structure.

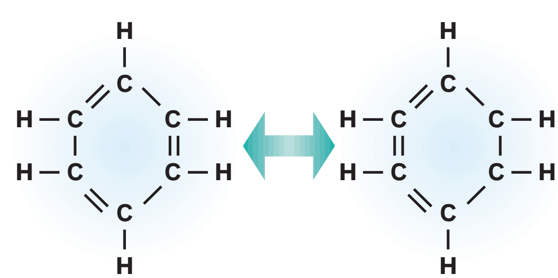


Table 2.7: Solubility of six-carbon compounds.

Compound	Solubility
Hexane	10 mg/L
Hexanol	5,900 mg/L
Cyclohexane	55 mg/L
Benzene	1780 mg/L
Phenol	82,000 mg/L
Chlorobenzene	448 mg/L

could also diffuse across cell membranes (which have, in part, a rather nonpolar character). The industry developed a parameter to quantify the polar versus nonpolar character of potential drugs, and they called that parameter the octanol-water partition coefficient. Basically they put water and octanol (an eight-carbon alcohol) into a vessel, added the organic compound of interest, and shook the combination up. After a period of rest, the water and octanol separate (neither is very soluble in the other), and the concentration of the organic compound can be measured in each phase. The *octanol-water partition coefficient*, or K_{ow}, is defined simply as:

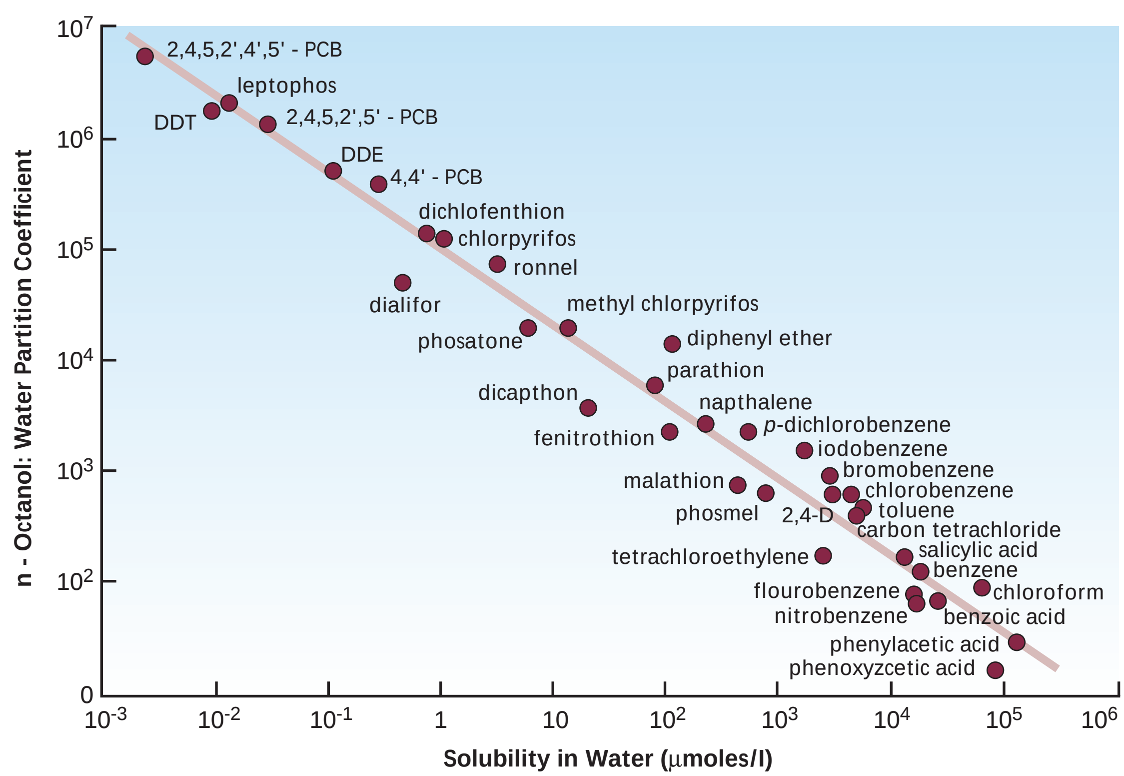
$$K_{ow} = \text{concentration in octanol} / \text{concentration in water}$$

The relation between water solubility and K_{ow} is shown in **Figure 2.24**. Generally we see that very insoluble compounds like DDT and PCBs have very high values of K_{ow}. Alternatively, organic acids and small organic solvents like TCE are relatively soluble and have low K_{ow} values.

The octanol-water partition coefficient has been determined for many compounds and can be useful in understanding the distribution of SOC

Figure 2.24: Relationship between octanol/H_2O partition coefficient and aqueous solubility.

The relative solubility in water is a substance's "Water Partition Coefficient."



between water and biota, and between water and sediments. Compounds with high K_{ow} tend accumulate in fish tissue (**Figure 2.25**). The *sediment-water distribution coefficient*, often expressed as K_d, is defined in a sediment-water mixture at equilibrium as the ratio of the concentration in the sediment to the concentration in the water:

K_d = concentration in sediment / concentration in water

One might ask whether this coefficient is constant for a given SOC. Values of K_d for two polyaromatic hydrocarbons in various soils are shown in **Figure 2.26**. For pyrene (which consists of four benzene rings stuck together), the K_d ratio vary from about 300 to 1500. For phenanthrene (which consists of three benzene rings stuck together), K_d varies from about 10 to 300. Clearly K_d is not a constant value for either compound. But, K_d does appear to bear a relation to the fraction of organic carbon in the various sediments. What appears to be constant is not K_d itself, but the ratio of K_d to the fraction of organic carbon in the sediment. This ratio is referred to as K_{oc}:

K_{oc} = K_d / fraction of organic carbon in sediment

Various workers have related K_{oc} to K_{ow} and to water solubility (**Table 2.8**).

Using K_{ow}, K_{oc}, and K_d to describe the partitioning of an SOC between water and sediment has shown some utility, but this approach is not applicable to the sorption of all organic molecules in all systems. Sorption of some SOC occurs by hydrogen bonding, such as occurs in cation exchange or metal

Figure 2.25: Relationship between octanol/water partition (P_{oct}) coefficient and bioaccumulation factor (BCF) in trout muscle.

Water quality can be inferred by the accumulation of contaminants in fish tissue.

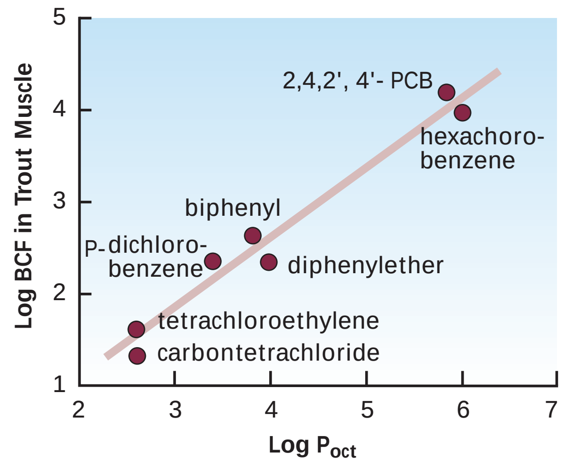


Figure 2.26: Relationship between pyrene, phenanthrene, and fraction organic carbon.

Contaminant concentrations in sediment vs. water (K_d) are related to the amount of organic carbon available.

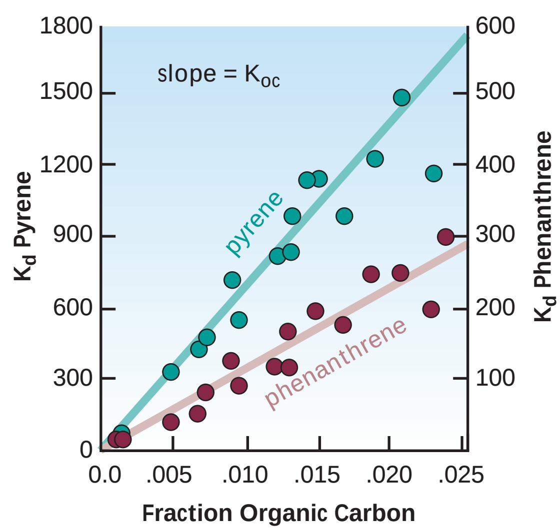


Table 2.8: Regression equations for sediment adsorption coefficients (K_{oc}) for various contaminants.

Equation[a]	No.[b]	r^2 [c]	Chemical Classes Represented
$\log K_{oc} = -0.55 \log S + 3.64$ (S in mg/L)	106	0.71	Wide variety, mostly pesticides
$\log K_{oc} = -0.54 \log S + 0.44$ (S in mole fraction)	10	0.94	Mostly aromatic or polynuclear aromatics; two chlorinated
$\log K_{oc} = -0.557 \log S + 4.277$ (S in μ moles/L)[d]	15	0.99	Chlorinated hydrocarbons
$\log K_{oc} = 0.544 \log K_{ow} + 1.377$	45	0.74	Wide variety, mostly pesticides
$\log K_{oc} = 0.937 \log K_{ow} - 0.006$	19	0.95	Aromatics, polynuclear aromatics, triazines and dinitroaniline herbicides
$\log K_{oc} = 1.00 \log K_{ow} - 0.21$	10	1.00	Mostly aromatic or polynuclear aromatics; two chlorinated
$\log K_{oc} = 0.95 \log K_{ow} + 0.02$	9	e	S-triazines and dinitroaniline herbicides
$\log K_{oc} = 1.029 \log K_{ow} - 0.18$	13	0.91	Variety of insecticides, herbicides and fungicides
$\log K_{oc} = 0.524 \log K_{ow} + 0.855$[d]	30	0.84	Substituted phenylureas and alkyl-N-phenylcarbamates
$\log K_{oc} = 0.0067 (p - 45N) + 0.237$[d,f]	29	0.69	Aromatic compounds, urea, 1.3.5-triazines, carbamates, and uracils
$\log K_{oc} = 0.681 \log 8CF(f) + 1.963$	13	0.76	Wide variety, mostly pesticides
$\log K_{oc} = 0.681 \log 8CF(t) + 1.886$	22	0.83	Wide variety, mostly pesticides

[a] K_{oc} = soil (or sediment) adsorption coefficient; S = water solubility; K_{ow} = octanol-water partition coefficient; BCF(f) = bioconcentration factor from flowing-water tests; BCF(t) = bioconcentration factor from model ecosystems; P = parachor; N = number of sites in molecule which can participate in the formation of a hydrogen bond.

[b] No. = number of chemicals used to obtain regression equation.

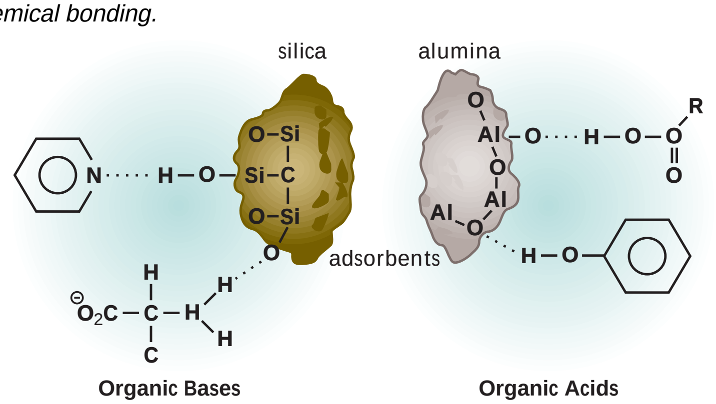
[c] r^2 = correlation coefficient for regression equation.

[d] Equation originally given in terms of K_{om}. The relationship $K_{om} = K_{oc}/1.724$ was used to rewrite the equation in terms of K_{oc}.

[e] Not available.

[f] Specific chemicals used to obtain regression equation not specified.

Figure 2.27: Two important types of hydrogen bonding involving natural organic matter and mineral surfaces. *Some contaminants are carried by sediment particles that are sorbed onto their surfaces by chemical bonding.*



sorption to sediments (**Figure 2.27**). Sorption is not always reversible; or at least after sorption occurs, desorption may be very slow.

Volatilization

Organic compounds partition from water into air by the process of volatilization. An air-water distribution coefficient, the Henry's Law constant (H), has been defined as the ratio of the concentration of a SOC in air in equilibrium with its concentration in water:

H = SOC concentration in air / SOC concentration in water

"SOC" = synthetic organic compounds

A Henry's Law constant for an SOC can be estimated from the ratio of the compound's vapor pressure to its water solubility. Organic compounds that are inherently volatile (generally low molecular weight solvents) have very high Henry's Law constants. But even compounds with very low vapor pressure can partition into the atmosphere. DDT and PCBs for example, have modest Henry's Law constants because their solubility in water is so low. These SOC also have high K_d values and so may become airborne in association with particulate matter.

Degradation

SOC can be transformed into a variety of degradation products. These degradation products may themselves degrade. Ultimate degradation, or mineralization, results in the oxidation of organic carbon to carbon dioxide. Major transformation processes include photolysis, hydrolysis, and oxidation-reduction reactions. The latter are commonly mediated by biological systems.

Photolysis refers to the destruction of a compound by the energy of light. The energy of light varies inversely with its wavelength (**Figure 2.28**). Long-wave light lacks sufficient energy to break chemical bonds. Short wave light (x-rays and gamma rays) is very destructive; fortunately for life on earth, this type of radiation largely is removed by our upper atmosphere. Light near the visible spectrum reaches the earth's surface and can break many of the bonds common in SOC. The fate of organic solvents following volatilization is usually photolysis in the earth's atmosphere. Photolysis also can be important in the degradation of SOC in stream water.

Hydrolysis refers to the splitting of an organic molecule by water. Essentially water enters a polar location on a molecule and inserts itself, with an H^+ going to one part of the parent molecule and an OH^- going to the other.

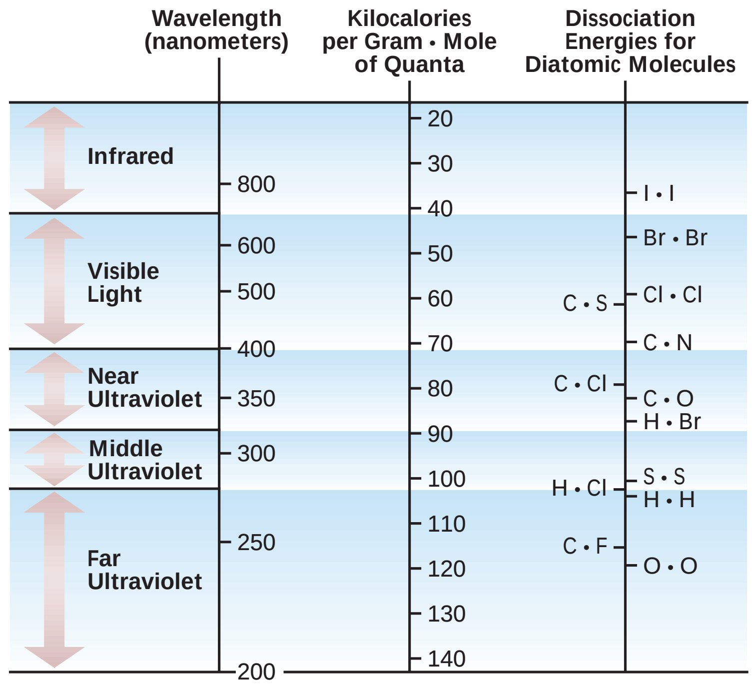


Figure 2.28: Energy of electromagnetic radiation compared with some selected bond energies.
Light breaks chemical bonds of some compounds through photolysis.

The two parts then separate. A group of SOC called esters are particularly vulnerable to degradation by hydrolysis. Many esters have been produced as pesticides or plasticizers.

Oxidation-reduction reactions are what fuels most metabolism in the biosphere. SOC are generally considered as sources of reduced carbon. In such situations, what is needed for degradation is a metabolic system with the appropriate enzymes for the oxidation of the compound. A sufficient supply of other nutrients and a terminal electron acceptor are also required.

The *principal of microbial infallibility* informally refers to the idea that given a supply of potential food, microbial communities will develop the metabolic capability to use that food for biochemical energy. Not all degradation reactions, however, involve the oxidation of SOC. Some of the most problematic organic contaminants are chlorinated compounds.

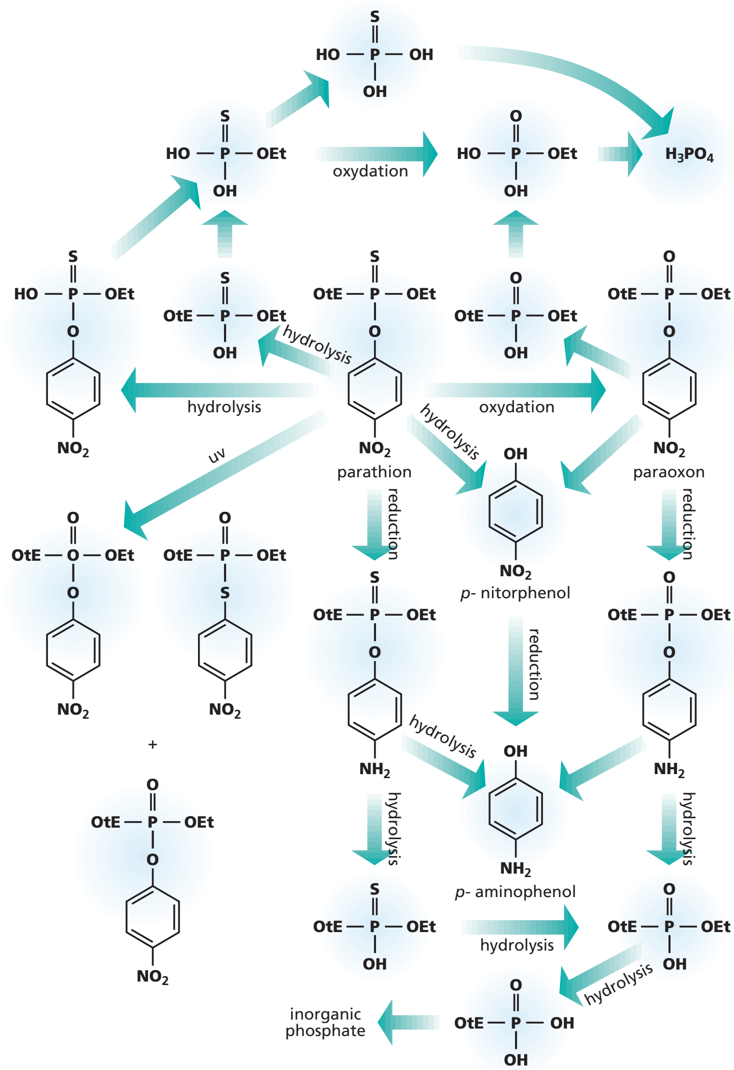


Figure 2.29: Metabolic reactions for a single parent pesticide.
Particles break down through processes of hydrolysis, oxidation, reduction, and photolysis.

Chlorinated SOC do not exist naturally, so microbial systems generally are not adapted for their degradation. Chlorine is an extremely electronegative element. The electronegativity of chlorine refers to its penchant for sucking on electrons. This tendency explains why chloride exists as an anion and why an attached chloride diminishes the solubility of an aromatic ring. Given this character, it is difficult for biological systems to oxidize chlorinated compounds. An initial step in that degradation, therefore, is often reductive dechlorination.

The chlorine is removed by reducing the compound (i.e., by giving it electrons). After the chlorines are removed, degradation may proceed along oxidative pathways. The degradation of chlorinated SOC thus may require a sequence of reducing and oxidizing environments, which water may experience as it moves between stream and hyporheic zones.

The overall degradation of SOC often follows complex pathways. **Figure 2.29** shows a complex web of metabolic reaction for a single parent pesticide. Hydrolysis, reduction, and oxidation are all involved in the degradation of SOC, and the distribution and behavior of degradation products can be extremely variable in space and time.

Chemical consequences are rarely the immediate goal of most restoration actions. Plans that alter chemical processes and attributes are usually focused on changing the physical and biological characteristics that are vital to the restoration goals.

Toxic Concentrations of Bioavailable Metals

A variety of naturally occurring metals, ranging from arsenic to zinc, have been established to be toxic to various forms of aquatic life when present in sufficient concentrations. The primary mechanisms for water column toxicity of most metals is adsorption at the gill surface. While some studies indicate that particulate metals may contribute to toxicity, perhaps because of factors such as desorption at the gill surface, the dissolved metal concentration most closely approximates the fraction of metal in the water column that is bioavailable. Accordingly, current EPA policy is that dissolved metal concentrations should be used to set and measure compliance with water quality standards (40 CFR 22228-22236, May 4, 1995). For most metals, the dissolved fraction is equivalent to the inorganic ionic fraction. For certain metals, most notably mercury, the dissolved fraction also may include the metal complexed with organic binding agents (e.g., methyl mercury, which can be produced in sediments by methanogenic bacteria, is soluble and highly toxic, and can accumulate through the food chain.)

Toxic Concentrations of Bioavailable Metals Across the Stream Corridor

Unlike synthetic organic compounds, toxic metals are naturally occurring. In common with synthetic organics, metals may be loaded to waterbodies from both point and nonpoint sources. Pollutants such as copper, zinc, and lead are often of concern in effluent from wastewater treatment plants but are required under the NPDES program to meet numeric water quality standards.

Many of the toxic metals are present at significant concentrations in most soils but in sorbed nonbioavailable forms. Sediment often introduces significant concentrations of metals such as zinc into waterbodies. It is then a matter of whether instream conditions promote bioavailable dissolved forms of the metal.

Nonpoint sources of metals first reflect the characteristics of watershed soils. In addition, many older industrial areas have soil concentrations of certain metals that are elevated due to past industrial practices. Movement of metals from soil to watershed is largely a function of the erosion and delivery of sediment.

In certain watersheds, a major source of metals loading is provided by acid mine drainage. High acidity increases the solubility of many metals, and mines tend to be in mineral-rich areas. Abandoned mines are therefore a continuing source of toxic metals loading in many streams.

Toxic Concentrations of Bioavailable Metals Along the Stream Corridor

Most metals have a tendency to leave the dissolved phase and attach to suspended particulate matter or form insoluble precipitates. Conditions that partition metals into particulate forms (presence of suspended sediments, dissolved and particulate organic carbon, carbonates, bicarbonates, and other ions that complex metals) reduce potential bioavailability of metals. Also, calcium reduces metal uptake, apparently by competing with metals for active uptake sites on gill membranes. pH is also an important water quality factor in metal bioavailability. In general, metal solubilities are lower at near neutral pH’s than in acidic or highly alkaline waters.

Ecological Functions of Soils

Soil is a living and dynamic resource that supports life. It consists of inorganic mineral particles of differing sizes (clay, silt, and sand), organic matter in various stages of decomposition, numerous species of living organisms, various water soluble ions and various gases and water. These components each have their own physical and chemical characteristics which can either support or restrict a particular form of life.

Soils can be mineral or organic depending on which material makes up the greater percentage in the soil matrix. Mineral soils develop in materials weathered from rocks while organic soils develop in decayed vegetation. Both soils typically develop horizons or layers that are approximately parallel to the soil surface. The extreme variety of specific niches or conditions soil can create has enabled a large variety of fauna and flora to evolve and live under those conditions.

Soils, particularly riparian and wetland soils, contain and support a very high diversity of flora and fauna both above and below the soil surface. A large variety of specialized organisms can be found below the soil surface, outnumbering those above ground by several orders of magnitude. Generally, organisms seen above ground are higher forms of life such as plants and wildlife. However, at and below ground, the vast majority of life consists of plant roots having the responsibility of supporting the above ground portion of the plant, many insects, mollusks, fungi living on dead organic matter, and an infinite number of bacteria which can live on a wide variety of energy sources found in soil.

It is important to identify soil boundaries and to understand the differences in soil properties and functions occurring within a stream corridor in order to identify opportunities and limitations for restoration. Floodplain and terrace soils are often areas of dense population and intensive agricultural development due to their flat slopes, proximity to water, and natural fertility. When planning stream corridor restoration initiatives in developed areas, it is important to recognize these alterations and to consider their impacts on goals.

Soils perform vital functions throughout the landscape. One of the most important functions of soil is to provide a physical, chemical, and biological setting for living organisms. Soils support biological activity and diversity for plant and animal productivity. Soils also regulate and partition the flow of water and the storage and cycling of nutrients and other elements in the landscape. They filter, buffer, degrade, immobilize, and detoxify organic and inorganic materials and provide the mechanical support living organisms need. These hydrologic, geomorphic, and biologic functions involve processes that help build and sustain stream corridors.

Soil Microbiology

Organic matter provides the main source of energy for soil microorganisms. Soil organic matter normally makes up 1 to 5 percent of the total weight in a mineral topsoil. It consists of original tissue, partially decomposed tissue, and humus. Soil organisms consume roots and vegetative detritus for energy and to build tissue. As the original organic matter is decomposed and modified by microorganisms, a gelatinous, more resistant compound is formed. This material is called *humus*. It is generally black or brown in color and exists as a colloid, a group of small, insoluble particles suspended in a gel. Small amounts of humus greatly increase a soil's ability to hold water and nutrient ions which enhances plant production. Humus is an indicator of a large and viable population of microorganisms in the soil and it increases the options available for vegetative restoration.

Bacteria play vital roles in the organic transactions that support plant growth. They are responsible for three essential transformations: denitrification, sulfur oxidation, and nitrogen fixation. Microbial reduction of nitrate to nitrite and then to gaseous forms of nitrogen is termed *denitrification*. A water content of 60 percent generally limits denitrification and the process only occurs at soil temperatures between 5°C and 75 °C. Other soil properties optimizing the rate of denitrification include a pH between 6 and 8, soil aeration below the biological oxygen demand of the organisms in the soil, sufficient amounts of water-soluble carbon compounds, readily available nitrate in the soil, and the presence of enzymes needed to start the reaction.

Landscape and Topographic Position

Soil properties change with topographic position. Elevation differences generally mark the boundaries of soils and drainage conditions in stream corridors. Different landforms generally have different types of sediment underlying them. Surface and subsurface drainage patterns also vary with landforms.

- *Soils of active channels.* The active channel forms the lowest and usually youngest surfaces in the stream corridor. There is generally no soil developed on these surfaces since the unconsolidated materials forming the stream bottom and banks are constantly being eroded, transported, and redeposited.
- *Soils of active floodplains.* The next highest surface in the stream corridor is the flat, depositional surface of the active floodplain. This surface floods frequently, every 2 out of 3 years, so it receives sediment deposition.
- *Soils of natural levees.* Natural levees are built adjacent to the stream by deposition of coarser, suspended sediment dropping out of overbank flows during floods. A gentle backslope occurs on the flood-plain side of the natural levee, so the floodplain becomes lowest at a point far from the river. Parent materials decrease in grain size away from the river due to the decrease in sediment-transport capacity in the slackwater areas.

- *Soils of topographic floodplains.* Slightly higher areas within and outside the active floodplain are defined as the topographic floodplain. They are usually inundated less frequently than the active floodplain, so soils may exhibit more profile development than the younger soils on the active floodplain.
- *Soils of terraces.* Abandoned floodplains, or terraces, are the next highest surfaces in stream corridors. These surfaces rarely flood. Terrace soils, in general, are coarser textured than floodplain soils, are more freely drained, and are separated from stream processes.

Upon close examination, floodplain deposits can reveal historical events of given watersheds. Soil profile development offers clues to the recent and geologic history at a site. Intricate and complex analysis methods such as carbon dating, pollen analysis, ratios of certain isotopes, etc. can be used to piece together an area's history. Cycles of erosion or deposition can at times be linked to catastrophic events like forest fires or periods of high or low precipitation. Historical impacts of civilization, such as extensive agriculture or denudation of forest cover will at times also leave identifiable evidence in soils.

Soil Temperature and Moisture Relationships

Soil temperature and moisture control biological processes occurring in soil. Average and expected precipitation and temperature extremes are critical pieces of information when considering goals for restoration initiatives. The mean annual soil temperature is usually very similar to the mean annual air temperature. Soil temperatures do experience daily, seasonal, and annual fluctuations caused by solar radiation, weather patterns, and climate. Soil temperatures are also affected by aspect, latitude, and elevation.

Soil moisture conditions change seasonally. If changes in vegetation species and composition are being considered as part of a restoration initiative, a graph comparing monthly precipitation and evapotranspiration for the vegetation should be constructed. If the water table and capillary fringe is below the predicted rooting depth, and the graph indicates a deficit in available water, irrigation may be required. If no supplemental water is available, different plant species must be considered.

The soil moisture gradient can decrease from 100 percent to almost zero along the transriparian continuum as one progresses from the stream bottom, across the riparian zone, and into the higher elevations of the adjacent uplands (Johnson and Lowe 1985), which results in vast differences in moisture available to vegetation. This gradient in soil moisture directly influences the characteristics of the ecological communities of the riparian, transitional, and upland zones. These ecological differences result in the presence of two ecotones along the stream corridor–an aquatic-wetland/riparian ecotone and a non-wetland riparian/floodplain ecotone–which increase the edge effect of the riparian zone and, therefore, the biological diversity of the region.

Wetland Soils

Wet or “hydric” soils present special challenges to plant life. Hydric soils are present in wetlands areas, creating such drastic changes in physical and chemical conditions that most species found in uplands cannot survive. Hence the composition of flora and fauna in wetlands are vastly different and unique, especially in wetlands subject to permanent or prolonged saturation or flooding.

Hydric soils are defined as those that are saturated, flooded or ponded long enough during the growing season to develop anaerobic conditions in the upper part. These anaerobic conditions affect the reproduction, growth and survival of plants. The driving process behind the formation of hydric soils is flooding and/or soil saturation near the surface for prolonged periods (usually more the seven days) during the growing season. (Tiner and Veneman 1989).

The following focuses primarily on mineral hydric soil properties, but organic soils such as peat and muck may be present in the stream corridor.

In aerated soil environments, atmospheric oxygen enters surface soils through gas diffusion, as soil pores are mostly filled with air. Aerated soils are found in well drained uplands, and generally all areas having a water table well below the root zone. In saturated soils, pores are filled with water, which diffuse gases very slowly compared to the atmosphere. Only small amounts of oxygen can dissolve in soil moisture, which then disperses into the top few inches of soil. Here, soil microbes quickly deplete all available free oxygen in oxidizing organic residue to carbon dioxide. This reaction produces an anaerobic chemically reducing environment in which oxidized compounds are changed to reduced compounds that are soluble and also toxic to many plants. The rate of diffusion is so slow that oxygenated conditions cannot be reestablished under such circumstances. Similar microbial reactions involving decomposition of organic matter in waterlogged anaerobic environments produce ethylene gas, which is highly toxic to plant roots and has an even stronger effect than a lack of oxygen. After all free oxygen is utilized, anaerobic microbes reduce other chemical constituents of the soil including nitrates, manganese oxides, and iron oxides, creating a further reduced condition in the soil.

Prolonged anaerobic reducing conditions result in the formation of readily visible signs of reduction. The typical gray colors encountered in wet soils are the result of reduced iron, and are known as *gleyed* soils. After iron oxides are depleted, sulfates are reduced to sulfides, producing the rotten egg odor of wet soils. Under extremely waterlogged conditions, carbon dioxide can be reduced to methane. Methane gas, also known as “swamp gas” can be seen at night, as it fluoresces.

Some wetland plants have evolved special mechanisms to compensate for having their roots immersed in anoxic environments. Water lilies, for example, force a gas exchange within the entire plant by closing their stomata during the heat of the day to raise the air pressure within special conductive tissue (aerenchyma). This process tends to introduce atmospheric oxygen deep into the root crown, keeping vital tissues alive. Most emergent wetland plants simply keep their root systems close to the soil surface to avoid anaerobic conditions in deeper strata. This is true of sedges and rushes, for example.

When soils are continually saturated throughout, reactions can occur equally throughout the soil profile as opposed to wet soils where the water level fluctuates. This produces soils with little zonation, and materials tend to be more uniform. Most differences in texture encountered with depth are related to stratification of sediments sorted by size during deposition by flowing water. Clay formation tends to occur in place and little translocation happens within the profile, as essentially no water moves through the soil to transport the particles. Due to the reactivity of wet soils, clay formation tends to progress much faster than in uplands.

Soils which are seasonally saturated or have a fluctuating water table result in distinct horizonation within the profile. As water regularly drains through the profile, it translocates particles and transports soluble ions from one layer to another, or entirely out of the profile. Often, these soils have a thick horizon near the surface which is stripped of all soluble materials including iron; known as a *depleted matrix*. Seasonally saturated soils usually have substantial organic matter accumulated at the surface, nearly black in color. The organics add to the cation exchange capacity of the soil, but base saturation is low due to stripping and overabundance of hydrogen ions. During non-saturated times, organic materials are exposed to atmospheric oxygen, and aerobic decomposition can take place which results in massive liberation of hydrogen ions. Seasonally wet soils also do not retain base metals well, and can release high concentrations of metals in wet cycles following dry periods.

Wet soil indicators will often remain in the soil profile for long periods of time (even after drainage), revealing the historical conditions which prevailed. Examples of such indicators are rust colored iron deposits which at one time were translocated by water in reduced form. Organic carbon distribution from past fluvial deposition cycles or zones of stripped soils resulting from wetland situations are characteristics which are extremely long lived.

Summary

This section provides only a brief overview of the diverse and complex chemistry; nevertheless, two key points should be evident to restoration practitioners:

- Restoring physical habitat cannot restore biological integrity of a system if there are water quality constraints on the ecosystem.
- Restoration activities may interact in a variety of complex ways with water quality, affecting both the delivery and impact of water quality stressors.

Table 2.9 shows how a sample selection of common stream restoration and watershed management practices may interact with the water quality parameters described in this section.

Table 2.9: Potential water quality impacts of selected stream restoration and watershed management practices.

Restoration Activities	Fine Sediment Loads	Water Temperature	Salinity	pH	Dissolved Oxygen	Nutrients	Toxics
Reduction of land-disturbing activities	Decrease	Decrease	Decrease	Increase/ decrease	Increase	Decrease	Decrease
Limit impervious surface area in the watershed	Decrease	Decrease	Negligible effect	Increase	Increase	Decrease	Decrease
Restore riparian vegetation	Decrease	Decrease	Decrease	Decrease	Increase	Decrease	Decrease
Restore wetlands	Decrease	Increase/ decrease	Increase/ decrease	Increase/ decrease	Decrease	Increase	Increase
Stabilize channel and restore under-cut banks	Decrease	Decrease	Decrease	Decrease	Increase	Decrease	Negligible effect
Create drop structures	Increase	Negligible effect	Negligible effect	Increase/ decrease	Increase	Negligible effect	Decrease
Re-establish riffle substrate	Negligible effect	Negligible effect	Negligible effect	Increase/ decrease	Increase	Negligible effect	Negligible effect

2.D Biological Community Characteristics

Successful stream restoration is based on an understanding of the relationships among physical, chemical, and biological processes at varying time scales. Often, human activities have accelerated the temporal progression of these processes, resulting in unstable flow patterns and altered biological structure and function of stream corridors. This section discusses the biological structure and functions of stream corridors in relation to geomorphologic, hydrologic, and water quality processes. The interrelations between the watershed and the stream, as well as the cause and effects of disturbances to these interrelationships are also discussed. Indices and approaches for evaluating stream corridor functions are provided in Chapter 7.

Terrestrial Ecosystems

The biological community of a stream corridor is determined by the characteristics of both terrestrial and aquatic ecosystems. Accordingly, the discussion of biological communities in stream corridors begins with a review of terrestrial ecosystems.

Ecological Role of Soil

Terrestrial ecosystems are fundamentally tied to processes within the soil. The ability of a soil to store and cycle nutrients and other elements depends on the properties and microclimate (i.e., moisture and temperature) of the soil, and the soil's community of organisms (**Table 2.10**). These factors

Table 2.10: Groups of organisms commonly present in soils.

Animals		
Macro	**Subsisting largely on plant materials**	
	Small mammals—squirrels, gophers, woodchucks, mice, shrews	
	Insects—springtails, ants, beetles, grubs, etc.	
	Millipedes	
	Sowbugs (woodlice)	
	Mites	
	Slugs and snails	
	Earthworms	
	Largely predatory	
	Moles	
	Insects—many ants, beetles, etc.	
	Mites, in some cases	
	Centipedes	
	Spiders	
Micro	**Predatory or parasitic or subsisting on plant residues**	
	Nematodes	
	Protozoa	
	Rotifers	

Plants		
Roots of higher plants		
Algae		
	Green	
	Blue-green	
	Diatoms	
Fungi		
	Mushroom fungi	
	Yeasts	
	Molds	
Actinomycetes of many kinds		
Bacteria		
	Aerobic	Autotropic
		Heterotropic
	Anaerobic	Autotropic
		Heterotropic

REVERSE

*See **Section C** for further discussion of the ecological functions of soils.*

also determine its effectiveness at filtering, buffering, degrading, immobilizing, and detoxifying other organic and inorganic materials.

Terrestrial Vegetation

The ecological integrity of stream corridor ecosystems is directly related to the integrity and ecological characteristics of the plant communities that make up and surround the corridor. These plant communities are a valuable source of energy for the biological communities, provide physical habitat, and moderate solar energy fluxes to and from the surrounding aquatic and terrestrial ecosystems. Given adequate moisture, light, and temperature, the vegetative community grows in an annual cycle of active growth/production, senescence, and relative dormancy. The growth period is subsidized by incidental solar radiation, which drives the photosynthetic process through which inorganic carbon is converted to organic plant materials. A portion of this organic material is stored as above- and below-ground biomass, while a significant fraction of organic matter is lost annually via senescence, fractionation, and leaching to the organic soil layer in the form of leaves, twigs, and decaying roots. This organic fraction, rich in biological activity of microbial flora and microfauna, represents a major storage and cycling pool of available carbon, nitrogen, phosphorus, and other nutrients.

The distribution and characteristics of vegetative communities are determined by climate, water availability, topographic features, and the chemical and physical properties of the soil, including moisture and nutrient content. The characteristics of the plant communities directly influence the diversity and integrity of the faunal communities. Plant communities that cover a large area and that are diverse in their vertical and horizontal structural characteristics can support far more diverse faunal communities than relatively homogenous plant communities, such as meadows. As a result of the complex spatial and temporal relationships that exist between floral and faunal communities, current ecological characteristics of these communities reflect the recent historical (100 years or less) physical conditions of the landscape.

The quantity of terrestrial vegetation, as well as its species composition, can directly affect stream channel characteristics. Root systems in the streambank can bind bank sediments and moderate erosion processes. Trees and smaller woody debris that fall into the stream can deflect flows and induce erosion at some points and deposition at others. Thus woody debris accumulation can influence pool distribution, organic matter and nutrient retention, and the formation of microhabitats that are important fish and invertebrate aquatic communities.

Streamflow also can be affected by the abundance and distribution of terrestrial vegetation. The short-term effects of removing vegetation can result in an immediate short-term rise in the local water table due to decreased evapotranspiration and additional water entering the stream. Over the longer term, however, after removal of vegetation, the baseflow of streams can decrease and water temperatures can rise, particularly in low-order streams. Also, removal of vegetation can cause changes in soil temperature and structure, resulting in decreased movement of water into and through the soil profile. The loss of surface litter and the gradual loss of organic matter in the soil also contribute to increased surface runoff and decreased infiltration.

In most instances, the functions of vegetation that are most apparent are those that influence fish and wildlife. At the landscape level, the fragmentation of native cover types has been shown to significantly influence wildlife, often favoring opportunistic species over those requiring large blocks of contiguous habitat. In some systems, relatively small breaks in corridor continuity can have significant impacts on animal movement or on the suitability of stream conditions to support certain aquatic species. In others, establishing corridors that are structurally different from native systems or that are inappropriately configured can be equally disruptive. Narrow corridors that are essentially edge habitat may encourage generalist species, nest parasites, and predators, and, where corridors have been established across historic barriers to animal movement, they can disrupt the integrity of regional animal assemblages (Knopf et al. 1988).

Landscape Scale

The ecological characteristics and distribution of plant communities in a watershed influence the movement of water, sediment, nutrients, and wildlife. Stream corridors provide links with other features of the landscape. Links may involve continuous corridors between headwater and valley floor ecosystems or periodic interactions between terrestrial systems. Wildlife use corridors to disperse juveniles, to migrate, and to move between portions of their home range. Corridors of a natural origin are preferred and include streams and rivers, riparian strips, mountain passes, isthmuses, and narrow straits (Payne and Bryant 1995).

It is important to understand the differences between a stream-riparian ecosystem and a river-floodplain ecosystem. Flooding in the stream-riparian ecosystem is brief and unpredictable. The riparian zone supplies nutrients, water, and sediment to the stream channel, and riparian vegetation regulates temperature and light. In the river-floodplain ecosystem, floods are often more predictable and longer lasting, the river channel is the donor of water, sediment and inorganic nutrients to the floodplain, and the influx of turbid and cooler channel water influences light penetration and temperature of the inundated floodplain.

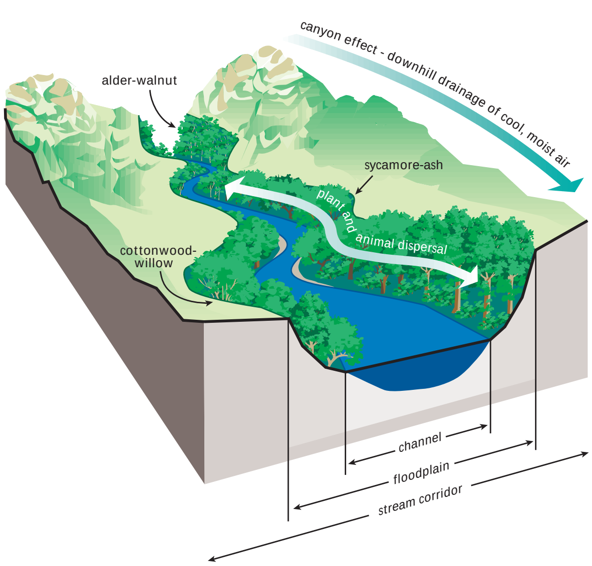
Stream Corridor Scale

At the stream corridor scale, the composition and regeneration patterns of vegetation are characterized in terms of *horizontal complexity*. Floodplains along unconstrained channels typically are vegetated with a mosaic of plant communities, the composition of which varies in response to available surface and ground water, differential patterns of flooding, fire, and predominant winds, sediment deposition, and opportunities for establishing vegetation.

A broad floodplain of the southern, midwestern, or eastern U.S. may support dozens of relatively distinct forest communities in a complex mosaic reflecting subtle differences in soil type and flood characteristics (e.g., frequency, depth, and duration). In contrast, while certain western stream systems may support only a few woody species, these systems may be structurally complex due to constant reworking of substrates by the stream, which produces a mosaic of stands of varying ages. The presence of side channels, oxbow lakes, and other topographic variation can be viewed as elements of structural variation at the stream corridor level. Riparian areas along constrained stream channels may consist primarily of upland vegetation organized by processes largely unrelated to stream characteristics, but these areas may have considerable influence on the stream ecosystem.

The River Continuum Concept, as discussed in Chapter 1, is also generally applicable to the vegetative components of the riparian corridor. Riparian vegetation demonstrates both a transriparian gradient (across the valley) and an intra-riparian (longitudinal, elevational) gradient (Johnson and Lowe 1985). In the west, growth of riparian vegetation is increased by the "canyon effect" resulting when cool moist air spills downslope from higher elevations (**Figure 2.30**). This cooler air settles in canyons and creates a more moist microhabitat than occurs on the surrounding slopes. These canyons also serve as water courses. The combination of moist, cooler edaphic and atmospheric conditions is conducive to plant and animal species at lower than normal altitudes, often in disjunct populations or in regions where they would not otherwise occur (Lowe and Shannon 1954).

Figure 2.30: Canyon effect.
Cool moist air settles in canyons and creates microhabitat that occurs on surrounding slopes.



Plant Communities

The sensitivity of animal communities to vegetative characteristics is well recognized. Numerous animal species are associated with particular plant communities, many require particular developmental stages of those communities (e.g., old-growth), and some depend on particular habitat elements within those communities (e.g., snags). The structure of streamside plant communities also directly affects aquatic organisms by providing inputs of appropriate organic materials to the aquatic food web, by shading the water surface and providing cover along banks, and by influencing instream habitat structure through inputs of woody debris (Gregory et al. 1991).

Plant communities can be viewed in terms of their internal complexity (**Figure 2.31**). Complexity may include the number of layers of vegetation and the species comprising each layer; competitive interactions among species; and the presence of detrital components, such as litter, downed wood, and snags. Vegetation may contain tree, sapling, shrub (subtree), vine, and herbaceous subshrub (herb-grass-forb) layers. Microtopographic relief and the ability of water to locally pond also may be regarded as characteristic structural components.

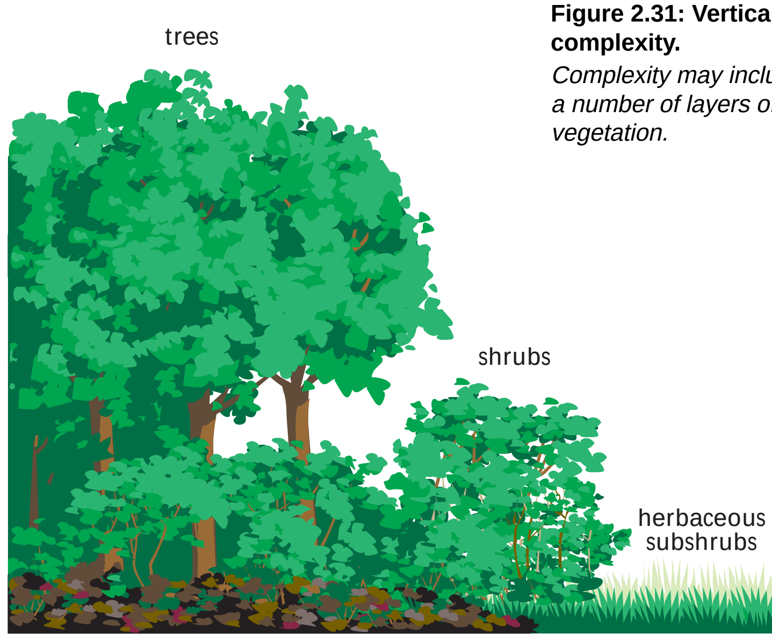


Figure 2.31: Vertical complexity.
Complexity may include a number of layers of vegetation.

Vertical complexity, described in the concept of diversity of strata or foliage height diversity in ecological literature, was important to studies of avian habitat by Carothers et al. (1974) along the Verde River, a fifth- or sixth-order stream in central Arizona. Findings showed a high correlation between riparian bird species diversity and foliage height diversity of riparian vegetation (Carothers et al. 1974). Short (1985) demonstrated that more structurally diverse vegetative habitats support a greater number of guilds (groups of species with closely related niches in a community) and therefore a larger number of species.

Species and age composition of vegetation structure also can be extremely important. Simple vegetative structure, such as an herbaceous layer without woody overstory or old woody riparian trees without smaller size classes, creates fewer niches for guilds. The fewer guilds there are, the fewer species there are. The quality and vigor of the vegetation can affect the productivity of fruits, seeds, shoots, roots, and other vegetative material, which provide food for wildlife. Poorer vigor can result in less food and fewer consumers (wildlife). Increasing the patch size (area) of a streamside vegetation type, increasing the number of woody riparian tree size classes, and increasing the number of species and growth forms (herb, shrub, tree) of native riparian-dependent vegetation can increase the number of guilds and the amount of forage, resulting in increased species richness and biomass (numbers). Restoration techniques can change the above factors.

The importance of horizontal complexity within stream corridors to certain animal species also has been well established. The characteristic compositional, structural, and topographic complexity of southern floodplain forests, for example, provides the range of resources and foraging conditions required by many wintering waterfowl to meet particular requirements of their life cycles at the appropriate times (Fredrickson 1978); similar complex relationships have been reported for other vertebrates and invertebrates in floodplain habitats (Wharton et al. 1982). In parts of the arid West, the unique vegetation structure in riparian systems contrasts dramatically with the surrounding uplands and provides essential habitat for many animals (Knopf et al. 1988). Even within compositionally simple riparian systems, different developmental stages may provide different resources.

Plant communities are distributed on floodplains in relation to flood depth, duration, and frequency, as well as variations in soils and drainage condition. Some plant species, such as cottonwood (*Populus* sp.), willows (*Salix* sp.), and silver maple (*Acer saccharinum*), are adapted to colonization of newly deposited sediments and may require very specific patterns of flood recession during a brief period of seedfall to be successfully established (Morris et al. 1978, Rood and Mahoney 1990). The resultant pattern is one of even-aged tree stands established at different intervals and locations within the active meander belt of the stream. Other species, such as the bald cypress (*Taxodium distichum*), are particularly associated with oxbow lakes formed when streams cut off channel segments, while still others are associated with microtopographic variations within floodplains that reflect the slow migration of a stream channel across the landscape.

Plant communities are dynamic and change over time. The differing regeneration strategies of particular vegetation types lead to characteristic patterns of plant succession following disturbances in which pioneer species well-adapted to bare soil and plentiful light are gradually replaced by longer-lived species that can regenerate under more shaded and protected conditions. New disturbances reset the successional process. Within stream corridors, flooding, channel migration, and, in certain biomes, fire, are usually the dominant natural sources of disturbance. Restoration practitioners should understand patterns of natural succession in a stream corridor and should take advantage of the successional process by planting hardy early-successional species to stabilize an eroding streambank, while planning for the eventual replacement of these species by longer-lived and higher-successional species.

Terrestrial Fauna

Stream corridors are used by wildlife more than any other habitat type (Thomas et al. 1979) and are a major source of water to wildlife populations, especially large mammals. For example, 60 percent of Arizona's wildlife species depend on riparian areas for survival (Ohmart and Anderson 1986). In the Great Basin area of Utah and Nevada, 288 of the 363 identified terrestrial vertebrate species depend on riparian zones (Thomas et al. 1979). Because of their wide suitability for upland and riparian species, midwestern stream corridors associated with prairie grasslands support a wider diversity of wildlife than the associated uplands. Stream corridors play a large role in maintaining biodiversity for all groups of vertebrates.

The faunal composition of a stream corridor is a function of the interaction of food, water, cover, and spatial arrangement (Thomas et al. 1979). These habitat components interact in multiple ways to provide eight habitat features of stream corridors:

- Presence of permanent sources of water.
- High primary productivity and biomass.
- Dramatic spatial and temporal contrasts in cover types and food availability.
- Critical microclimates.
- Horizontal and vertical habitat diversity.
- Maximized edge effect.
- Effective seasonal migration routes.
- High connectivity between vegetated patches.

Stream corridors offer the optimal habitat for many forms of wildlife because of the proximity to a water source and an ecological community that consists primarily of hardwoods in many parts of the country, which provide a source of food, such as nectar, catkins, buds, fruit, and seeds (Harris 1984). Upstream sources of water, nutrients, and energy ultimately benefit downstream locations. In turn, the fish and wildlife return and disperse some of the nutrients and energy to uplands and wetlands during their movements and migrations (Harris 1984).

Water is especially critical to fauna in areas such as the Southwest or Western Prairie regions of the U.S. where stream corridors are the only naturally occurring permanent sources of water on the landscape. These relatively moist environments contribute to the high primary productivity and biomass of the riparian area, which contrasts dramatically with surrounding cover types and food sources. In these areas, stream corridors provide critical microclimates that ameliorate the temperature and moisture extremes of uplands by providing water, shade, evapotranspiration, and cover.

The spatial distribution of vegetation is also a critical factor for wildlife. The linear arrangement of streams results in a maximized edge effect that increases species richness because a species can simultaneously access more than one cover (or habitat) type and exploit the resources of both (Leopold 1933). Edges occur along multiple habitat types including the aquatic, riparian, and upland habitats.

Forested connectors between habitats establish continuity between forested uplands that may be surrounded by unforested areas. These act as feeder lines for dispersal and facilitate repopulation by plants and animals. Thus, connectivity is very important for retaining biodiversity and genetic integrity on a landscape basis.

However, the linear distribution of habitat, or edge effect, is not an effective indicator of habitat quality for all species. Studies in island biogeography, using habitat islands rather than oceanic islands, demonstrate that a larger habitat island supports both a larger population of birds and also a larger number of species (Wilson and Carothers 1979). Although a continuous corridor is most desirable, the next preferable situation is minimal fragmentation, i.e., large plots ("islands") of riparian vegetation with minimal spaces between the large plots.

Reptiles and Amphibians

Nearly all amphibians (salamanders, toads, and frogs) depend on aquatic habitats for reproduction and overwintering. While less restricted by the presence of water, many reptiles are found primarily in stream corridors and riparian habitats. Thirty-six of the 63 reptile and amphibian species found in west-central Arizona were found to use riparian zones. In the Great Basin, 11 of 22 reptile species require or prefer riparian zones (Ohmart and Anderson 1986).

Birds

Birds are the most commonly observed terrestrial wildlife in riparian corridors. Nationally, over 250 species have been reported using riparian areas during some part of the year.

The highest known density of nesting birds in North America occurs in southwestern cottonwood habitats (Carothers and Johnson 1971). Seventy-three percent of the 166 breeding bird species in the Southwest prefer riparian habitats (Johnson et al. 1977).

Bird species richness in midwestern stream corridors reflects the vegetative diversity and width of the corridor. Over half of these breeding birds are species that forage for insects on foliage (vireos, warblers) or species that forage for seeds on the ground (doves, orioles, grosbeaks, sparrows). Next in abundance are insectivorous species that forage on the ground or on trees (thrushes, woodpeckers).

Smith (1977) reported that the distribution of bird species in forested habitats of the Southeast was closely linked to soil moisture. Woodcock (*Scolopax minor*) and snipe (*Gallinago gallinago*), red-shouldered hawks (*Buteo lineatus*), hooded and prothonotary warblers (*Wilsonia citrina*, *Protonotaria citrea*), and many other passerines in the Southeast prefer the moist ground conditions found in riverside forests and shrublands for feeding. The cypress and mangrove swamps along Florida’s waterways harbor many species found almost nowhere else in the Southeast.

Mammals

The combination of cover, water, and food resources in riparian areas make them desirable habitat for large mammals such as mule deer (*Odocoileus hemionus*), white-tailed deer (*Odocoileus virginianus*), moose (*Alces alces*), and elk (*Cervus elaphus*) that can use multiple habitat types. Other mammals depend on riparian areas in some or all of their range. These include otter (*Lutra canadensis*), ringtail (*Bassarisdus astutus*), raccoon (*Procyon lotor*), beaver (*Castor canadensis*), muskrat (*Ondatra zibethicus*), swamp rabbit (*Sylvilagus aquaticus*), short-tailed shrew (*Blarina brevicauda*), and mink (*Mustela vison*).

Riparian areas provide tall dense cover for roosts, water, and abundant prey for a number of bat species, including the little brown bat (*Myotis lucifugus*), big brown bat (*Eptesicus fuscus*), and the pallid bat (*Antrozous pallidus*). Brinson et al. (1981) tabulated results from several studies on mammals in riparian areas of the continental U.S. They concluded that the number of mammal species generally ranges from five to 30, with communities including several furbearers, one or more large mammals, and a few small to medium mammals.

Hoover and Wills (1984) reported 59 species of mammals in cottonwood riparian woodlands of Colorado, second only to pinyon-juniper among eight other forested cover types in the region. Fifty-two of the 68 mammal species found in west-central Arizona in Bureau of Land Management inventories use riparian habitats. Stamp and Ohmart (1979) and Cross (1985) found that riparian areas had a greater diversity and biomass of small mammals than adjacent upland areas.

The contrast between the species diversity and productivity of mammals in the riparian zone and that of the surrounding uplands is especially high in arid and semiarid regions. However, bottomland hardwoods in the eastern U.S. also have exceptionally high habitat values for many mammals. For example, bottomland hardwoods support white-tail deer populations roughly twice as large as equivalent areas of upland forest (Glasgow and Noble 1971).

Stream corridors are themselves influenced by certain animal activities (Forman 1995). For example, beavers build dams that cause ponds to form within a stream channel or in the floodplain. The pond kills much of the existing vegetation, although it does create wetlands and open water areas for fish and migratory waterfowl. If appropriate woody plants in the floodplain are scarce, beavers extend their cutting activities into the uplands and can significantly alter the riparian and stream corridors. Over time, the pond is replaced by a mudflat, which becomes a meadow and eventually gives way to woody successional stages. Beaver often then build a dam at a new spot, and the cycle begins anew with only a spatial displacement.

The sequence of beaver dams along a stream corridor may have major effects on hydrology, sedimentation, and mineral nutrients (Forman 1995). Water from stormflow is held back, thereby affording some measure of flood control. Silts and other fine sediments accumulate in the pond rather than being washed downstream. Wetland areas usually form, and the water table rises upstream of the dam. The ponds combine slow flow, near-constant water levels, and low turbidity that support fish and other aquatic organisms. Birds may use beaver ponds extensively. The wetlands also have a relatively constant water table, unlike the typical fluctuations across a floodplain. Beavers cutting trees diminish the abundance of such species as elm (*Ulmus* spp.) and ash (*Fraxinus* spp.) but enhance the abundance of rapidly sprouting species, such as alder (*Alnus* spp.), willow, and poplar (*Populus* spp.).

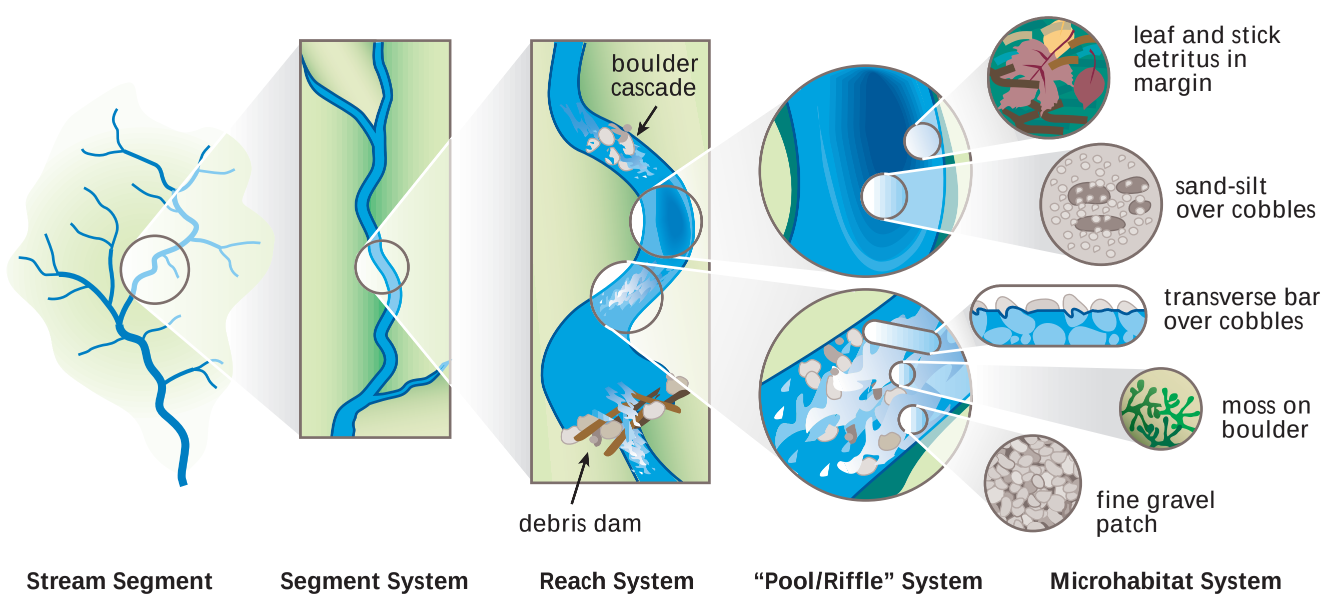
Aquatic Ecosystems

Aquatic Habitat

The biological diversity and species abundance in streams depend on the diversity of available habitats. Naturally functioning, stable stream systems promote the diversity and availability of habitats. This is one of the primary reasons stream stability and the restoration of natural functions are always considered in stream corridor restoration activities. A stream's cross-sectional shape and dimensions, its slope and confinement, the grain-size distribution of bed sediments, and even its planform affect aquatic habitat. Under less disturbed situations, a narrow, steep-walled cross section provides less physical area for habitat than a wider cross section with less steep sides, but may provide more biologically rich habitat in deep pools compared to a wider, shallower stream corridor. A steep, confined stream is a high-energy environment that may limit habitat occurrence, diversity, and stability. Many steep, fast flowing streams are coldwater salmonid streams of high value. Unconfined systems flood frequently, which can promote riparian habitat development. Habitat increases with stream sinuosity. Uniform sediment size in a streambed provides less potential habitat diversity than a bed with many grain sizes represented.

Habitat subsystems occur at different scales within a stream system (Frissell et al. 1986) (**Figure 2.32**). The grossest scale, the stream system itself, is measured in thousands of feet, while segments are measured in hundreds of feet and reaches are measured in tens of feet. A reach system includes combinations of debris dams, boulder cascades, rapids, step/pool sequences, pool/riffle sequences, or other types of streambed forms or "structures," each of which could be 10 feet or less in scale. Frissell's smallest scale habitat subsystem includes features that are a foot or less in size. Examples of these *microhabitats* include leaf or stick detritus, sand or silt over cobbles or other coarse material, moss on boulders, or fine gravel patches.

Figure 2.32: Hierarchical organization of a stream system and its habitat subsystems. *Approximate linear spatial scale, appropriate to second- or third-order mountain stream.*



Steep slopes often form a step/pool sequence in streams, especially in cobble, boulder, and bedrock streams. Each step acts as a miniature grade stabilization structure. The steps and pools work together to distribute the excess energy available in these steeply sloping systems. They also add diversity to the habitat available. Cobble- and gravel-bottomed streams at less steep slopes form pool/riffle sequences, which also increase habitat diversity. Pools provide space, cover, and nutrition to fish and they provide a place for fish to seek shelter during storms, droughts, and other catastrophic events. Upstream migration of many salmonid species typically involves rapid movements through shallow areas, followed by periods of rest in deeper pools (Spence et al. 1996).

Wetlands

Stream corridor restoration initiatives may include restoration of wetlands such as riverine-type bottomland hardwood systems or riparian wetlands. While wetland restoration is a specific topic better addressed in other references (e.g., Kentula 1992), a general discussion of wetlands is provided here. Stream corridor restoration initiatives should be designed to protect or restore the functions of associated wetlands.

A wetland is an ecosystem that depends on constant or recurrent shallow inundation or saturation at or near the surface of the substrate. The minimum essential characteristics of a wetland are recurrent, sustained inundation or saturation at or near the surface and the presence of physical, chemical, and biological features that reflect recurrent sustained inundation or saturation. Common diagnostic features of wetlands are hydric soils and hydrophytic vegetation. These features will be present except where physicochemical, biotic, or anthropogenic factors have removed them or prevented their development (National Academy of Sciences 1995). Wetlands may occur in streams, riparian areas, and floodplains of the stream corridor. The riparian area or zone may contain both wetlands and non-wetlands.

Wetlands are transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water (Cowardin et al. 1979). For vegetated wetlands, water creates conditions that favor the growth of hydrophytes—plants growing in water or on a substrate that is at least periodically deficient in oxygen as a result of excessive water content (Cowardin et al. 1979) and promotes the development of hydric soils—soils that are saturated, flooded, or ponded long enough during the growing season to develop anaerobic conditions in the upper part (National Academy of Sciences 1995).

Wetland functions include fish and wildlife habitat, water storage, sediment trapping, flood damage reduction, water quality improvement/pollution control, and ground water recharge. Wetlands have long been recognized as highly productive habitats for threatened and endangered fish and wildlife species. Wetlands provide habitat for 60 to 70 percent of the animal species federally listed as threatened or endangered (Lohoefner 1997).

Riparian Mapping

The riparian zone is a classic example of the maximized value that occurs when two or more habitat types meet. There is little question of the substantial value of riparian habitats in the United States. The Fish and Wildlife Service has developed protocols to classify and map riparian areas in the West in conjunction with the National Wetlands Inventory (NWI). NWI will map riparian areas on a 100 percent user-pay basis. No formal riparian mapping effort has been initiated. The NWI is congressionally mandated to identify, classify, and digitize all wetlands and deepwater habitats in the United States. For purposes of riparian mapping, the NWI has developed a riparian definition that incorporates biological information consistent with many agencies and applies information according to cartographic principles. For NWI mapping and classification purposes, a final definition for riparian has been developed:

"Riparian areas are plant communities contiguous to and affected by surface and subsurface hydrological features of perennial or intermittent lotic and lentic water bodies (rivers, streams, lakes, and drainage ways). Riparian areas have one or both of the following characteristics: (1) distinctly different vegetative species than adjacent areas; and (2) species similar to adjacent areas but exhibiting more vigorous or robust growth forms. Riparian areas are usually transitional between wetland and upland."

The definition applies primarily to regions of the lower 48 states in the arid west where the mean annual precipitation is 16 inches or less and the mean annual evaporation exceeds mean annual precipitation. For purposes of this mapping, the riparian system is subdivided into subsystems, classes, subclasses, and dominance types. (USFWS 1997)

The Federal Geographic Data Committee has adopted the U.S. Fish and Wildlife Service's *Classification of Wetlands and Deepwater Habitats of the United States* (Cowardin, et al. 1979) as the national standard for wetlands classification. The Service's National Wetlands Inventory (NWI) uses this system to carry out its congressionally mandated role of identifying, classifying, mapping, and digitizing data on wetlands and deepwater habitats. This system, which defines wetlands consistently with the National Academy of Science's reference definition, includes Marine, Estuarine, Riverine, Lacustrine, and Palustrine systems. The NWI has also developed protocols for classifying and mapping riparian habitats in the 22 coterminous western states.

The riverine system under Cowardin's classification includes all wetlands and deepwater habitats contained within a channel except wetlands dominated by trees, shrubs, persistent emergents, emergent mosses, or lichens and habitats with water containing ocean-derived salts in excess of 0.5 parts per thousand (ppt).

It is bounded on the upstream end by uplands and on the downstream end at the interface with tidal wetlands having a concentration of ocean-derived salts that exceeds 0.5 ppt. Riverine wetlands are bounded perpendicularly on the landward side by upland, the channel bank (including natural and manufactured levees) or by *Palustrine wetlands*. In braided streams, riverine wetlands are bounded by the banks forming the outer limits of the depression within which the braiding occurs.

Vegetated floodplain wetlands of the river corridor are classified as Palustrine under this system. The Palustrine system was developed to group the vegetated wetlands traditionally called by such names as marsh, swamp, bog, fen, and prairie pothole and also includes small, shallow, permanent, or intermittent water bodies often called ponds. Palustrine wetlands may be situated shoreward of lakes, river channels, or estuaries, on river floodplains, in isolated catchments, or on slopes. They also may occur as islands in lakes or rivers. The Palustrine system includes all nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses and lichens, and all such wetlands that occur in tidal areas where salinity due to ocean-derived salts is below 0.5 ppt. The Palustrine system is bounded by upland or by any of the other four systems. They may merge with non-wetland riparian habitat where hydrologic conditions cease to support wetland vegetation or may be totally absent where hydrologic conditions do not support wetlands at all (Cowardin 1979).

The *hydrogeomorphic (HGM) approach* is a system that classifies wetlands into similar groups for conducting functional assessments of wetlands. Wetlands are classified based on geomorphology, water source and hydrodynamics. This allows the focus to be placed on a group of wetlands that function much more similarly than would be the case without classifying them. Reference wetlands are used to develop reference standards against which a wetland is evaluated (Brinson 1995).

Under the HGM approach, riverine wetlands occur in floodplains and riparian corridors associated with stream channels. The dominant water sources are overbank flow or subsurface connections between stream channel and wetlands. Riverine wetlands lose water by surface and subsurface flow returning to the stream channel, ground water recharge, and evapotranspiration. At the extension closest to the headwaters, riverine wetlands often are replaced by slope or depressional wetlands where channel bed and bank disappear, or they may intergrade with poorly drained flats and uplands. Usually forested, they extend downstream to the intergrade with estuarine fringe wetlands. Lateral extent is from the edge of the channel perpendicularly to the edge of the floodplain. In some landscape situations, riverine wetlands may function hydrologically more like slope wetlands, and in headwater streams with little or no floodplain, slope wetlands may lie adjacent to the stream channel (Brinson et al. 1995). **Table 2.11** summarizes functions of riverine wetlands under the HGM approach. The U.S. Fish and Wildlife Service is testing an operational draft set of hydrogeomorphic type descriptors to help bridge the gap between the Cowardin system and the HGM approach (Tiner 1997).

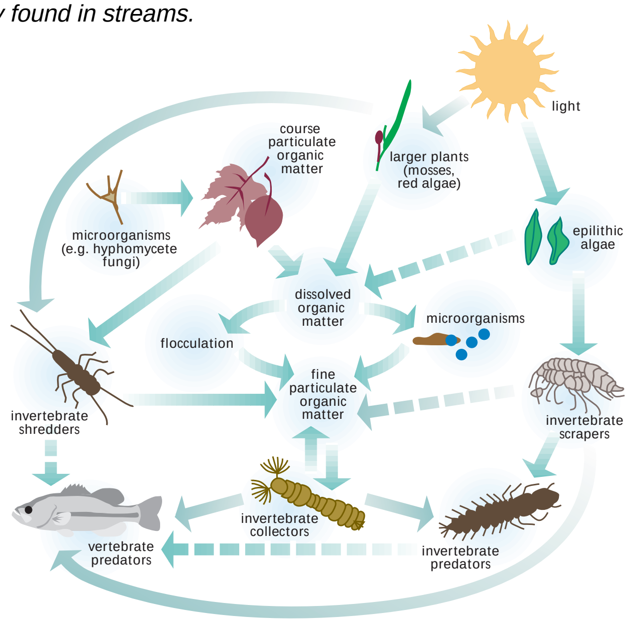
For purposes of regulation under Section 404 of the Clean Water Act, only areas with wetland hydrology,

Table 2.11: Functions of riverine wetlands.

Source: Brinson et al., 1995.

Hydrologic	Dynamic surface water storage
	Long-term surface water storage
	Subsurface storage of water
	Energy dissipation
	Moderation of ground-water flow or discharge
Biogeochemical	Nutrient cycling
	Removal of elements and compounds
	Retention of particulates
	Organic carbon export
Plant habitat	Maintain characteristic plant communities
	Maintain characteristic detrital biomass
Animal habitat	Maintain spatial habitat structure
	Maintain interspersion and connectivity
	Maintain distribution and abundance of invertebrates
	Maintain distribution and abundance of vertebrates

Figure 2.33: Stream biota.
Food relationships typically found in streams.



hydrophytic vegetation, and hydric soils are classified as regulated wetlands. As such, they represent a subset of the areas classified as wetlands under the Cowardin system. However, many areas classified as wetlands under the Cowardin system, but not classified as wetlands for purposes of Section 404, are nevertheless subject to regulation because they are part of the Waters of the United States.

Aquatic Vegetation and Fauna

Stream biota are often classified in seven groups—bacteria, algae, macrophytes (higher plants), protists (amoebas, flagellates, ciliates), microinvertebrates (invertebrates less than 0.02 inch in length, such as rotifers, copepods, ostracods, and nematodes), macroinvertebrates (invertebrates greater than 0.02 inch in length, such as mayflies, stoneflies, caddisflies, crayfish, worms, clams, and snails), and vertebrates (fish, amphibians, reptiles, and mammals) (**Figure 2.33**). The discussion of the River Continuum Concept in Chapter 1, provides an overview of the major groups of organisms found in streams and how these assemblages change from higher order to lower order streams.

Undisturbed streams can contain a remarkable number of species. For example, a comprehensive inventory of stream biota in a small German stream, the Breitenbach, found more than 1,300 species in a 1.2-mile reach. Lists of algae, macroinvertebrates, and fish likely to be found at potential restoration sites may be obtained from state or regional inventories. The densities of such stream biota are shown in **Table 2.12**.

Table 2.12: Ranges of densities commonly observed for selected groups of stream biota.

Biotic Component	Density (Individuals/Square Mile)
Algae	$10^9 - 10^{10}$
Bacteria	$10^{12} - 10^{13}$
Protists	$10^8 - 10^9$
Microinvertebrates	$10^3 - 10^5$
Macroinvertebrates	$10^4 - 10^5$
Vertebrates	$10^0 - 10^2$

Aquatic plants usually consist of algae and mosses attached to permanent stream substrates. Rooted aquatic vegetation may occur where substrates are suitable and high currents do not scour the stream bottom. Luxuriant beds of vascular plants may grow in some areas such as spring-fed streams in Florida where water clarity, substrates, nutrients, and slow water velocities exist. Bedrock or stones that cannot be moved easily by stream currents are often covered by mosses and algae and various forms of micro- and macroinvertebrates (Ruttner 1963). Planktonic plant forms are usually limited but may be present where the watershed contains lakes, ponds, floodplain waters, or slow current areas (Odum 1971).

The benthic invertebrate community of streams may contain a variety of biota, including bacteria, protists, rotifers, bryozoans, worms, crustaceans, aquatic insect larvae, mussels, clams, crayfish, and other forms of invertebrates. Aquatic invertebrates are found in or on a multitude of microhabitats in streams including plants, woody debris, rocks, interstitial spaces of hard substrates, and soft substrates (gravel, sand, and muck). Invertebrate habitats exist at all vertical strata including the water surface, the water column, the bottom surface, and deep within the hyporheic zone.

Unicellular organisms and microinvertebrates are the most numerous biota in streams. However, larger macroinvertebrates are important to community structure because they contribute significantly to a stream's total invertebrate biomass (Morin and Nadon 1991, Bourassa and Morin 1995). Furthermore, the larger species often play important roles in determining community composition of other components of the ecosystem. For example, herbivorous feeding activities of caddisfly larvae (Lamberti and Resh 1983), snails (Steinman et al. 1987), and crayfish (Lodge 1991) can have a significant effect on the abundance and taxonomic composition of algae and periphyton in streams. Likewise, macroinvertebrate predators, such as stoneflies, can influence the abundance of other species within the invertebrate community (Peckarsky 1985).

Collectively, microorganisms (fungi and bacteria) and benthic invertebrates facilitate the breakdown of organic material, such as leaf litter, that enters the stream from external sources. Some invertebrates (insect larvae and amphipods) act as shredders whose feeding activities break down larger organic leaf litter to smaller particles. Other invertebrates filter smaller organic material from the water (blackfly larvae, some mayfly nymphs, and some caddisfly larvae), scrape material off surfaces (snails, limpets, and some caddisfly and mayfly nymphs) or feed on material deposited on the substrate (dipteran larvae and some mayfly nymphs) (Moss 1988). These feeding activities result in the breakdown of organic matter in addition to the elaboration of invertebrate tissue, which other consumer groups, such as fish, feed on.

Benthic macroinvertebrates, particularly aquatic insect larvae and crustaceans, are widely used as indicators of stream health and condition. Many fish species rely on benthic organisms as a food source either by direct browsing on the benthos or by catching benthic organisms that become dislodged and drift downstream (Walburg 1971).

Fish are ecologically important in stream ecosystems because they are usually the largest vertebrates and often are the apex predator in aquatic systems. The numbers and species composition of fishes in a given stream depends on the geographic location, evolutionary history, and such intrinsic factors as physical habitat (current, depth, substrates, riffle/pool ratio, wood snags and undercut banks), water quality (temperature, dissolved oxygen, suspended solids, nutrients, and toxic chemicals), and biotic interactions (exploitation, predation, and competition).

There are approximately 700 native freshwater species of fish in North America (Briggs 1986). Fish species richness is highest in the Mississippi River Basin where most of the adaptive radiations have occurred in the United States (Allan 1995). In the Midwest, as many as 50 to 100 species can occur in a local area, although typically only half the species native to a region may be found at any one location (Horwitz 1978). Fish species richness generally declines as one moves westward across the U.S., primarily due to extinction during and following the Pleistocene Age (Fausch et al. 1984). For example, 210 species are found west of the Continental Divide, but only 40 of these species are found on both sides of the continent (Minckley and Douglas 1991). The relatively depauperate fauna of the Western U.S. has been attributed to the isolating mechanisms of tectonic geology. Secondary biological, physical, and chemical factors may further reduce the species richness of a specific community (Minckley and Douglas 1991, Allan 1995).

Fish species assemblages in streams will vary considerably from the headwaters to the outlet due to changes in many hydrologic and geomorphic factors which control temperature, dissolved oxygen, gradient, current velocity, and substrate. Such factors combine to determine the degree of habitat diversity in a given stream segment. Fish species richness tends to increase downstream as gradient decreases and stream size increases. Species richness is generally lowest at small headwater streams due to increased gradient and small stream size, which increases the frequency and severity of environmental fluctuations (Hynes 1970, Matthews and Styron 1980). In addition, the high gradient and decreased links with tributaries reduces the potential for colonization and entry of new species.

Species richness increases in mid-order to lower stream reaches due to increased environmental stability, greater numbers of potential habitats, and increases in numbers of colonization sources or links between major drainages. As one proceeds downstream, pools and runs increase over riffles, allowing for an increase in fine bottom materials and facilitating the growth of macrophytic vegetation. These environments allow for the presence of fishes more tolerant of low oxygen and increased temperatures. Further, the range of body forms increases with the appearance of those species with less fusiform body shapes, which are ecologically adapted to areas typified by decreased water velocities. In higher order streams or large rivers the bottom substrates often are typified by finer sediments; thus herbivores, omnivores, and planktivores may increase in response to the availability of aquatic vegetation and plankton (Bond 1979).

Fish have evolved unique feeding and reproductive strategies to survive in the diverse habitat conditions of North

America. Horwitz (1978) examined the structure of fish feeding guilds in 15 U.S. river systems and found that most fish species (33 percent) were benthic insectivores, whereas piscivores (16 percent), herbivores (7 percent), omnivores (6 percent), planktivores (3 percent), and other guilds contained fewer species. However, Allan (1995) indicated that fish frequently change feeding habits across habitats, life stages, and season to adapt to changing physical and biological conditions. Fish in smaller headwater streams tend to be insectivores or specialists, whereas the number of generalists and the range of feeding strategies increases downstream in response to increasing diversity of conditions

Some fish species are migratory, returning to a particular site over long distances to spawn. Others may exhibit great endurance, migrating upstream against currents and over obstacles such as waterfalls. Many must move between salt water and freshwater, requiring great osmoregulatory ability (McKeown 1984). Species that return from the ocean environment into freshwater streams to spawn are called *anadromous* species.

Species generally may be referred to as cold water or warm water, and gradations between, depending on their temperature requirements (Magnuson et al. 1979). Fish such as salmonids are usually restricted to higher elevations or northern climes typified by colder, highly oxygenated water. These species tend to be specialists, with rather narrow thermal tolerances and rather specific reproductive requirements. For example, salmonids typically spawn by depositing eggs over or within clean gravels which remain oxygenated and silt-free due to upwelling of currents within the interstitial spaces. Reproductive movement and behavior is controlled by subtle thermal changes combined with increasing or decreasing daylength. Salmonid populations, therefore, are highly susceptible to many forms of habitat degradation, including alteration of flows, temperature, and substrate quality.

Numerous fish species in the U.S. are declining in number. Williams et al. (1989) presented a list of North American fish species that the American Fisheries Society believed should be classified as endangered, threatened, or of special concern. This list contains 364 fish species warranting protection because of their rarity. Habitat loss was the primary cause of depletion for approximately 90 percent of the species listed. This study noted that 77 percent of the fish species listed were found in 25 percent of the states, with the highest concentrations in eight southwestern states. Nehlsen et al. (1991) provided a list of 214 native naturally spawning stocks of depleted Pacific salmon, steelhead, and sea-run cutthroat stocks from California, Oregon, Idaho, and Washington. Reasons cited for the declines were alteration of fish passage and migration due to dams, flow reduction associated with hydropower and agriculture, sedimentation and habitat loss due to logging and agriculture, overfishing, and negative interactions with other fish, including nonnative hatchery salmon and steelhead.

The widespread decline in the numbers of native fish species has led to current widespread interest in restoring the quality and quantity of habitats for fish. Restoration activities have frequently centered on improving local habitats, such as fencing or removing livestock from streams, constructing fish passages, or installing instream physical habitat. However, research has demonstrated that in most of these cases the success has been limited or questionable because the focus was too narrow and did not address restoration of the diverse array of habitat requirements and resources that are needed over the life span of a species.

Stream corridor restoration practitioners and others are now acutely aware that fish require many different habitats over the season and lifespan to fulfill needs for feeding, resting, avoiding predators, and reproducing. For example, Livingstone and Rabeni (1991) determined that juvenile smallmouth bass in the Jacks Fork River of southeastern Missouri fed primarily on small macroinvertebrates in littoral vegetation. Vegetation represented not only a source of food but a refuge from predators and a warmer habitat, factors that can collectively optimize chances for survival and growth (Rabeni and Jacobson 1993). Adult smallmouth bass, however, tended to occupy deeper pool habitats, and the numbers and biomass of adults at various sites were attributed to these specific deep-water habitats (McClendon and Rabeni 1987). Rabeni and Jacobson (1993) suggested that an understanding of these specific habitats, combined with an understanding of the fluvial hydraulics and geomorphology that form and maintain them, are key to developing successful stream restoration initiatives.

The emphasis on fish community restoration is increasing due to many ecological, economic, and recreational factors. In 1996 approximately 35 million Americans older than 16 participated in recreational fishing, resulting in over $36 billion in expenditures (Brouha 1997). Much of this activity is in streams, which justifies stream corridor restoration initiatives.

While fish stocks often receive the greatest public attention, preservation of other aquatic biota may also may be a goal of stream restoration. Freshwater mussels, many species of which are threatened and endangered, are often of particular concern (Williams et al. 1992). Mussels are highly sensitive to habitat disturbances and obviously benefit from intact, well-managed stream corridors. The south-central United States has the highest diversity of mussels in the world. Mussel ecology also is intimately linked with fish ecology, as fish function as hosts for mussel larvae (glochidia). Among the major threats they face are dams, which lead to direct habitat loss and fragmentation of remaining habitat, persistent sedimentation, pesticides, and introduced exotic species, such as fish and other mussel species.

Abiotic and Biotic Interrelations in the Aquatic System

Much of the spatial and temporal variability of stream biota reflects variations in both abiotic and biotic factors, including water quality, temperature, streamflow and flow velocity, substrate, the availability of food and nutrients, and predator-prey relationships. These factors influence the growth, survival, and reproduction of aquatic organisms. While these factors are addressed individually below, it is important to remember that they are often interdependent.

Flow Condition

The flow of water from upstream to downstream distinguishes streams from other ecosystems. The spatial and temporal characteristics of streamflow, such as fast versus slow, deep versus shallow, turbulent versus smooth, and flooding versus low flows, are described previously in this chapter. These flow characteristics can affect both micro- and macro-distribution patterns of numerous stream species (Bayley and Li 1992, Reynolds 1992, Ward 1992). Many organisms are sensitive to flow velocity because it represents an important mechanism for delivering food and nutrients yet also may limit the ability of organisms to remain in a stream segment. Some organisms also respond to temporal variations in flow, which can change the physical structure of the stream channel, as well as increase mortality, modify available resources, and disrupt interactions among species (Resh et al. 1988, Bayley and Li 1992).

The flow velocity in streams determines whether planktonic forms can develop and sustain themselves. The slower the currents in a stream, the more closely the composition and configuration of biota at the shore and on the bottom approach those of standing water. High flows are cues for timing migration and spawning of some fishes. High flows also cleanse and sort streambed materials and scour pools. Extreme low flows may limit young fish production because such flows often occur during periods of recruitment and growth (Kohler and Hubert 1993).

Water Temperature

Water temperature can vary markedly within and among stream systems as a function of ambient air temperature, altitude, latitude, origin of the water, and solar radiation (Ward 1985, Sweeney 1993). Temperature governs many biochemical and physiological processes in cold-blooded aquatic organisms because their body temperature is the same as the surrounding water; thus, water temperature has an important role in determining growth, development, and behavioral patterns. Stream insects, for example, often grow and develop more rapidly in warmer portions of a stream or during warmer seasons. Where the thermal differences among sites are significant (e.g., along latitudinal or altitudinal gradients), it is possible for some species to complete two or more generations per year at warmer sites; these same species complete one or fewer generations per year at cooler sites (Sweeney 1984, Ward 1992). Growth rates for algae and fish appear to respond to temperature changes in a similar fashion (Hynes 1970, Reynolds 1992). The relationships between temperature and growth, development, and behavior can be strong enough to affect geographic ranges of some species (**Table 2.13**).

Table 2.13: Maximum weekly average temperatures for growth and short term maximum temperatures for selected fish (°C and °F).

Source: Brungs and Jones 1977.

Species	Max. Weekly Average Temp. for Growth (Juveniles)	Max. Temp. for Survival of Short Exposure (Juveniles)	Max. Weekly Average Temp. for Spawning[a]	Max. Temp. for Embryo Spawning[b]
Atlantic salmon	68ºF	73ºF	41ºF	52ºF
Bluegill	90ºF	95ºF	77ºF	93ºF
Brook trout	66ºF	75ºF	48ºF	55ºF
Common carp			70ºF	91ºF
Channel catfish	90ºF	95ºF	81ºF	84ºF[c]
Largemouth bass	90ºF	93ºF	70ºF	81ºF[c]
Rainbow trout	66ºF	75ºF	48ºF	55ºF
Smallmouth bass	84ºF		63ºF	73ºF[c]
Sockeye salmon	64ºF	72ºF	50ºF	55ºF

[a] Optimum or mean of the range of spawning temperatures reported for the species.
[b] Upper temperature for successful incubation and hatching reported for the species.
[c] Upper temperature for spawning.

Water temperature is one of the most important factors determining the distribution of fish in freshwater streams, due both to direct impacts and influence on dissolved oxygen concentrations, and is influenced by local conditions, such as shade, depth and current. Many fish species can tolerate only a limited temperature range. Such fish as salmonids and sculpins dominate in cold water streams, whereas such species as largemouth bass, smallmouth bass, suckers, minnows, sunfishes and catfishes may be present in warmer streams (Walburg 1971).

Effects of Cover

For the purposes of restoration, land use practices that remove overhead cover or decrease baseflows can increase instream temperatures to levels that exceed critical thermal maxima for fishes (Feminella and Matthews 1984). Thus, maintenance or restoration of normal temperature regimes can be an important endpoint for stream managers.

Riparian vegetation is an important factor in the attenuation of light and temperature in streams (Cole 1994). Direct sunlight can significantly warm streams, particularly during summer periods of low flow. Under such conditions, streams flowing through forests warm rapidly as they enter deforested areas, but may also cool somewhat when streams reenter the forest. In Pennsylvania (Lynch et al. 1980), average daily stream temperatures that increased 12 °C through a clearcut area were substantially moderated after flow through 1,640 feet of forest below the clearcut. They attributed the temperature reduction primarily to inflows of cooler ground water.

A lack of cover also affects stream temperature during the winter. Sweeney (1993) found that, while average daily temperatures were higher in a second-order meadow stream than in a comparable wooded reach from April through October, the reverse was true from November through March. In a review of temperature effects on stream macroinvertebrates common to the Pennsylvania Piedmont, Sweeney (1992) found that temperature changes of 2 to 6 °C usually altered key life-history characteristics of the study species. Riparian forest buffers have been shown to prevent the disruption of natural temperature patterns as well as to mitigate the increases in temperature following deforestation (Brown and Krygier 1970, Brazier and Brown 1973).

The exact buffer width needed for temperature control will vary from site to site depending on such factors as stream orientation, vegetation, and width. Along a smaller, narrow head-water stream, the reestablishment of shrubs, e.g., willows and alders, may provide adequate shade and detritus to restore both the riparian and aquatic ecosystems. The planting and/or reestablishment of large trees, e.g., cottonwoods, willows, sycamores, ash, and walnuts (Lowe 1964), along larger, higher order rivers can improve the segment of the fishery closest to the banks, but has little total effect on light and temperature of wider rivers.

Heat budget models can accurately predict stream and river temperatures (e.g., Beschta 1984, Theurer et al. 1984). Solar radiation is the major factor influencing peak summer water temperatures and shading is critical to the overall temperature regime of streams in small watersheds.

Dissolved Oxygen

Oxygen enters the water by absorption directly from the atmosphere and by plant photosynthesis (Mackenthun 1969). Due to the shallow depth, large surface exposure to air and constant motion, streams generally contain an abundant dissolved oxygen supply even when there is no oxygen production by photosynthesis.

Dissolved oxygen at appropriate concentrations is essential not only to keep aquatic organisms alive but to sustain their reproduction, vigor, and development. Organisms undergo stress at reduced oxygen levels that make them less competitive in sustaining the species (Mackenthun 1969). Dissolved oxygen concentrations of 3.0 mg/l or less have been shown to interfere with fish populations for a number of reasons (Mackenthun 1969, citing several other sources) (**Table 2.14**).

Level of Effect	Salmonid[a]	Nonsalmonid
Early life stages (eggs and fry)		
No production impairment	11 (8)	6.5
Slight production impairment	9 (6)	5.5
Moderate production impairment	8 (5)	5.0
Severe production impairment	7 (4)	4.5
Limit to avoid acute mortality	6 (3)	4.0
Other life stages		
No production impairment	8 (0)	6.0
Slight production impairment	6 (0)	5.0
Moderate production impairment	5 (0)	4.0
Severe production impairment	4 (0)	3.5
Limit to avoid acute mortality	3 (0)	3.0

[a] Values for salmonid early life stages are water column concentrations recommended to achieve the required concentration of dissolved oxygen in the gravel spawning substrate (shown in parentheses).

Table 2.14: Summary of dissolved oxygen concentrations (mg/L) generally associated with effects on fish in salmonid and nonsalmonid waters.

Source: USEPA 1987.

Depletion of dissolved oxygen can result in the death of aquatic organisms, including fish. Fish die when the demand for oxygen by biological and chemical processes exceeds the oxygen input by reaeration and photosynthesis, resulting in fish suffocation. Oxygen depletion usually is associated with slow current, high temperature, extensive growth of rooted aquatic plants, algal blooms, or high concentrations of organic matter (Needham 1969).

Stream communities are susceptible to pollution that reduces the dissolved oxygen supply (Odum 1971). Major factors determining the amount of oxygen found in water are temperature, pressure, abundance of aquatic plants and the amount of natural aeration from contact with the atmosphere (Needham 1969). A level of 5 mg/l of dissolved oxygen in water is associated with normal activity of most fish (Walburg 1971). Oxygen analyses of good trout streams show dissolved oxygen concentrations that range from 4.5 to 9.5 mg/l (Needham 1969).

pH

Aquatic organisms from a wide range of taxa exist and thrive in aquatic systems with nearly neutral hydrogen ion activity (pH 7). Deviations, either toward a more basic or acidic environment, increase chronic stress levels and eventually decrease species diversity and abundance (**Figure 2.34**). One of the more widely recognized impacts of changes in pH has been attributed to increased acidity of rainfall in some parts of the United States, especially areas downwind of industrial and urban emissions (Schreiber 1995). Of particular concern are environments that have a reduced capacity to neutralize acid inputs because soils have a limited buffering capacity. Acidic rainfall can be especially harmfull to environments such as the Adirondack region of upstate New York, where runoff already tends to be slightly acidic as a result of natural conditions.

Substrate

Stream biota respond to the many abiotic and biotic variables influenced by substrate. For example, differences in species composition and abundance can be observed among macroinvertebrate assemblages found in snags, sand, bedrock, and cobble within a single stream reach (Benke et al. 1984, Smock et al. 1985, Huryn and Wallace 1987). This preference for conditions associated with different substrates contributes to patterns observed at larger spatial scales where different macroinvertebrate assemblages are found in coastal, piedmont, and mountain streams (Hackney et al. 1992).

Stream substrates can be viewed in the same functional capacity as soils in the terrestrial system; that is, stream substrates constitute the interface between water and the hyporheic subsurface of the aquatic system. The *hyphorheic zone* is the area of substrate which lies below the substrate/ water interface, and may range from a layer extending only inches beneath and laterally from the stream channel, to a very large subsurface environment. Alluvial floodplains of the Flathead River, Montana, have a hyphorheic zone with significant

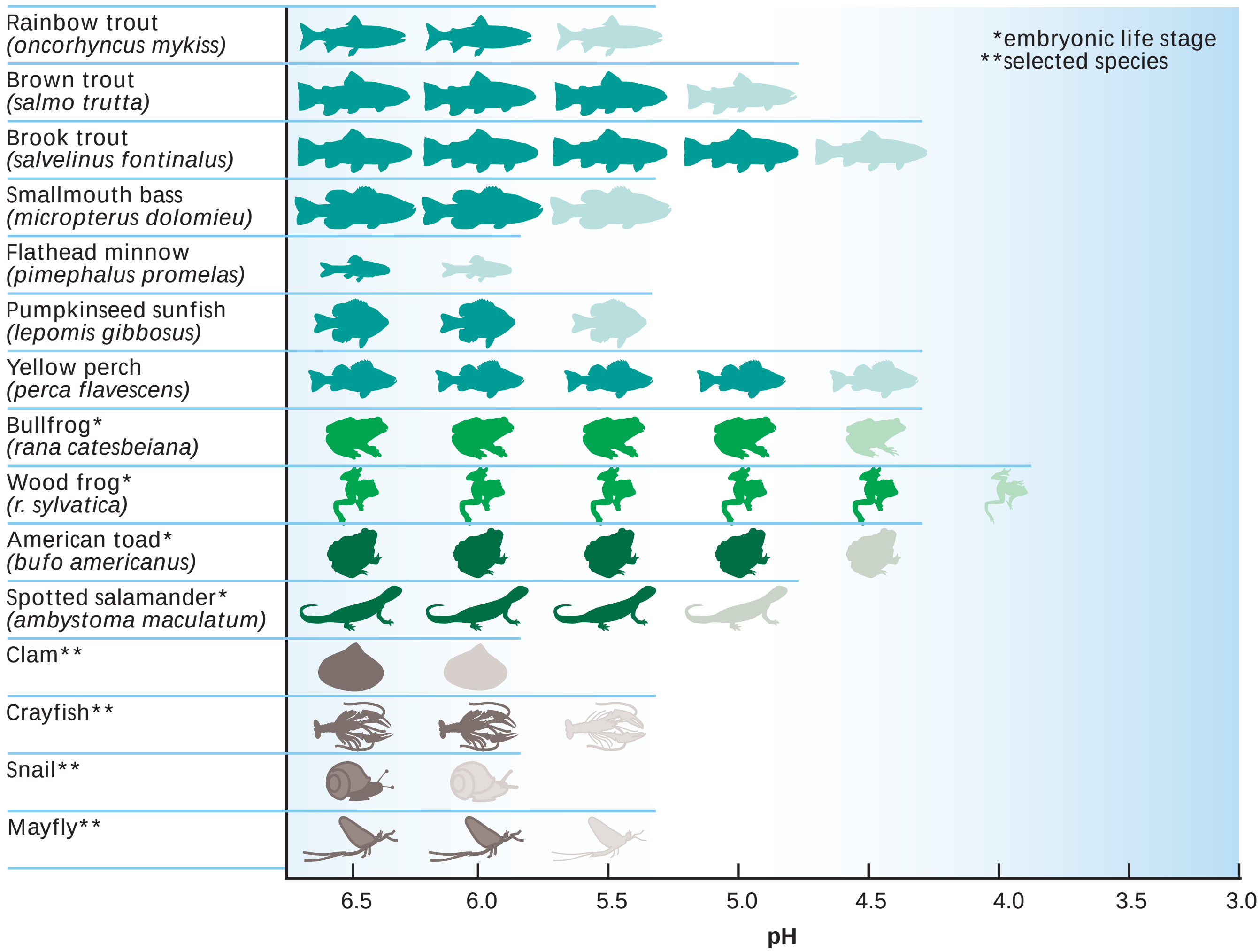


Figure 2.34: Effects of acid rain on some aquatic species.
As acidity increases (and pH decreased) in lakes and streams, some species are lost.

surface water/ground water interaction which is 2 miles wide and 33 feet deep (Stanford and Ward 1988). Naiman et al. (1994) discussed the extent and connectivity of hyphorheic zones around streams in the Pacific Northwest. They hypothesized that as one moves from low-order (small) streams to high-order (large) streams, the degree of hyphorheic importance and continuity first increases and then decreases. In small streams, the hyphorheic zone is limited to small floodplains, meadows, and stream segments where coarse sediments are deposited over bedrock. The hyphorheic zones are generally not continuous. In mid-order channels with more extensive floodplains, the spatial connectivity of the hyphorheic zone increases. In large order streams, the spatial extent of the hyphorheic zone is usually greatest, but it tends to be highly discontinuous because of features associated with fluvial activities such as oxbow lakes and cutoff channels, and because of complex interactions of local, intermediate, and regional ground water systems (Naiman et al. 1994) (**Figure 2.35**).

Stream substrates are composed of various materials, including clay, sand, gravel, cobbles, boulders, organic matter, and woody debris. Substrates

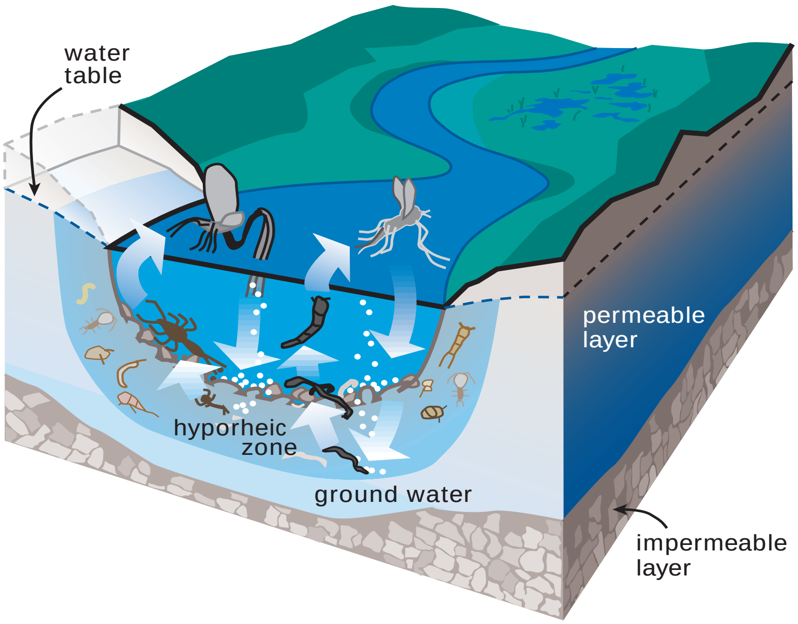


Figure 2.35: Hyphorheic zone.
Summary of the different means of migration undergone by members of the stream benthic community.

form solid structures that modify surface and interstitial flow patterns, influence the accumulation of organic materials, and provide for production, decomposition, and other processes (Minshall 1984). Sand and silt are generally the least favorable substrates for supporting aquatic organisms and support the fewest species and individuals. Flat or rubble substrates have the highest densities and the most organisms (Odum 1971). As previously described, substrate size, heterogeneity, stability with respect to high and baseflow, and durability vary within streams, depending on particle size, density, and kinetic energy of flow. Inorganic substrates tend to be larger upstream than downstream and tend to be larger in riffles than in pools (Leopold et al. 1964). Likewise, the distribution and role of woody debris varies with stream size (Maser and Sedell 1994).

In forested watersheds, and in streams with significant areas of trees in their riparian corridor, large woody debris that falls into the stream can increase the quantity and diversity of substrate and aquatic habitat or range (Bisson et al. 1987, Dolloff 1994). Debris dams trap sediment behind them and often create scour holes immediately downstream. Eroded banks commonly occur at the boundaries of debris blockages.

Organic Material

Metabolic activity within a stream reach depends on autochthonous, allochthonous, and upstream sources of food and nutrients (Minshall et al. 1985). Autochthonous materials, such as algae and aquatic macrophytes, originate within the stream channel, whereas allochthonous materials such as wood, leaves, and dissolved organic carbon, originate outside the stream channel. Upstream materials may be of autochthonous or allochthonous origin and are transported by streamflow to downstream locations. Seasonal flooding provides allochthonous input of organic material to the stream channel and also can significantly increase the rate of decomposition of organic material.

The role of primary productivity of streams can vary depending on geographic location, stream size, and season (Odum 1957, Minshall 1978). The river continuum concept (Vannote et al. 1980) (see *The River Continuum Concept* in section 1.E in Chapter 1) hypothesizes that primary productivity is of minimal importance in shaded headwater streams but increases in significance as stream size increases and riparian vegetation no longer limits the entry of light to stream periphyton. Numerous researchers have demonstrated that primary productivity is of greater importance in certain ecosystems, including streams in grassland and desert ecosystems. Flora of streams can range from diatoms in high mountain streams to dense stands of macrophytes in low gradient streams of the Southeast.

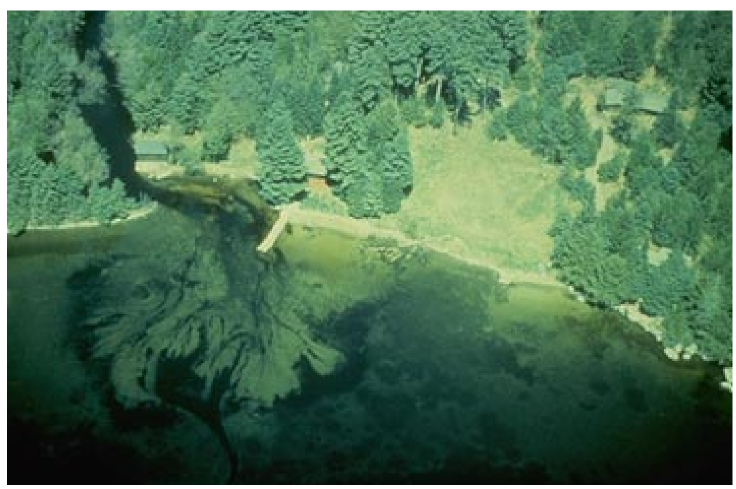
As discussed in Section 2.C, loading of nitrogen and phosphorus to a stream can increase the rate of algae and aquatic plant growth, a process known as *eutrophication*. Decomposition of this excess organic matter can deplete oxygen reserves and result in fish kills and other aesthetic problems in waterbodies.

Eutrophication in lakes and reservoirs is indirectly measured as standing crops of phytoplankton biomass, usually represented by planktonic chlorophyll a concentration. However, phytoplankton biomass is usually not the dominant portion of plant biomass in smaller streams, due to periods of energetic flow and high substrate to volume ratios that favor the development of periphyton and macrophytes on the stream bottom. Stream eutrophication can result in excessive algal mats and oxygen depletion at times of decreased flows and higher temperatures (**Figure 2.36**). Furthermore, excessive plant growth can occur in streams at apparently low ambient concentrations of nitrogen and phosphorus because the stream currents promote efficient exchange of nutrients and metabolic wastes at the plant cell surface.

In many streams, shading or turbidity limit the light available for algal growth, and biota depend highly on allochthonous organic matter, such as leaves and twigs produced in the surrounding watershed. Once leaves or other allochthonous materials enter the stream, they undergo rapid changes (Cummins 1974). Soluble organic compounds, such as sugars, are removed via leaching. Bacteria and fungi subsequently colonize the leaf materials and metabolize them as a source of carbon. The presence of the microbial biomass increases the protein content of the leaves, which ultimately represents a high quality food resource for shredding invertebrates.

The combination of microbial decomposition and invertebrate shredding/scraping reduces the average particle size of the organic matter, resulting in the loss of carbon both as respired CO_2 and as smaller organic particles transported downstream. These finer particles, lost from one stream segment, become the energy inputs to the downstream portions of the stream. This unidirectional movement of nutrients and organic matter in lotic systems is slowed by the temporary retention, storage, and utilization of nutrients in leaf packs, accumulated debris, invertebrates, and algae.

Figure 2.36: Stream eutrophication.
Eutrophication can result in oxygen depletion.



Organic matter processing has been shown to have nutrient-dependent relationships similar to primary productivity. Decomposition of leaves and other forms of organic matter can be limited by either nitrogen or phosphorus, with predictive N:P ratios being similar to those for growth of algae and periphyton. Leaf decomposition occurs by a sequential combination of microbial decomposition, invertebrate shredding, and physical fractionation. Leaves and organic matter itself are generally low in protein value. However, the colonization of organic matter by bacteria and fungi increases the net content of nitrogen and phosphorus due to the accumulation of proteins and lipids contained in microbial biomass. These compounds are a major nutritive source for aquatic invertebrates. Decaying organic matter represents a major storage component for nutrients in streams, as well as a primary pathway of energy and nutrient transfer within the food web. Ultimately, the efficiency of retention and utilization is reflected at the top of the food web in the form of fish biomass.

Organisms often respond to variations in the availability of autochthonous, allochthonous, and upstream sources. For example, herbivores are relatively more common in streams having open riparian canopies and high algal productivity compared to streams having closed canopies and accumulated leaves as the primary food resource (Minshall et al. 1983). Similar patterns can be observed longitudinally within the same stream (Behmer and Hawkins 1986).

Terrestrial and Aquatic Ecosystem Components for Stream Corridor Restoration

The previous sections presented the biological components and functional processes that shape stream corridors. The terrestrial and aquatic environments were discussed separately for the sake of simplicity and ease of understanding. Unfortunately, this is frequently the same approach taken in environmental restoration initiatives, with efforts placed separately on the uplands, riparian area, or instream channel. The stream corridor must be viewed as a single functioning unit or ecosystem with numerous connections and interactions between components. Successful stream corridor restoration cannot ignore these fundamental relationships.

The structure and functions of vegetation are interrelated at all scales. They are also directly tied to ecosystem dynamics. Particular vegetation types may have characteristic regeneration strategies (e.g., fire, treefall gaps) that maintain those types within the landscape at all times. Similarly, certain topographic settings may be more likely than others to be subject to periodic, dramatic changes in hydrology and related vegetation structure as a result of massive debris jams or occupation by beavers. However, in the context of stream corridor ecosystems, some of the most fundamental dynamic interactions relate to stream flooding and channel migration.

Many ecosystem functions are influenced by the structural characteristics of vegetation. In an undeveloped watershed, the movement of water and other materials is moderated by vegetation and detritus, and nutrients are mobilized and conserved in complex patterns that generally result in balanced interactions between terrestrial and aquatic systems. As the character and distribution of vegetation is altered by removal of biomass, agriculture, livestock grazing, development, and other land uses, and the flow patterns of water, sediment, and nutrients are modified, the interactions among system components become less efficient and effective. These problems can become more pronounced when they are aggravated by introductions of excess nutrients and synthetic toxins, soil disturbances, and similar impacts.

Stream migration and flooding are principal sources of structural and compositional variation within and among plant communities in most undisturbed floodplains (Brinson et al., 1981). Although streams exert a complex influence on plant communities, vegetation directly affects the integrity and characteristics of stream systems. For example, root systems bind bank sediments and moderate erosion processes, and floodplain vegetation slows overbank flows, inducing sediment deposition. Trees and smaller woody debris that fall into the channel deflect flows, inducing erosion at some points and deposition at others, alter pool distribution, the transport of organic material, as well as a number of other processes. The stabilization of streams that are highly interactive with their floodplains can disrupt the fundamental processes controlling the structure and function of stream corridor ecosystems, thereby indirectly affecting the characteristics of the surrounding landscape.

In most instances, the functions of vegetation that are most apparent are those that influence fish and wildlife. At the landscape level, the fragmentation of native cover types has been shown to significantly influence wildlife, often favoring opportunistic species over those requiring large blocks of contiguous habitat. In some systems, relatively small breaks in corridor continuity can have significant impacts on animal movement or on the suitability of stream conditions to support certain aquatic species. In others, establishment of corridors that are structurally different from native systems or inappropriately configured can be equally disruptive. Narrow corridors that are essentially edge habitat may encourage generalist species, nest parasites, and predators, and where corridors have been established across historic barriers to animal movement, they can disrupt the integrity of regional animal assemblages (Knopf et al. 1988).

Some riparian dependent species are linked to streamside riparian areas with fairly contiguous dense tree canopies. Without new trees coming into the population, older trees creating this linked canopy eventually drop out, creating ever smaller patches of habitat. Restoration that influences tree stands so that sufficient recruitment and patch size can be attained will benefit these species. For similar reasons, many riparian-related raptors such as the common black-hawk (*Buteogallus anthracinus*), gray hawk (*Buteo nitidus*), bald eagle (*Haliaeetus leucocephalus*), Cactus ferruginous pygmy-owl (*Glaucidium brasilianum cactorum*), and Cooper's hawk (*Accipiter cooperii*), depend upon various sizes and shapes of woody riparian trees for nesting substrate and roosts. Restoration practices that attain sufficient tree recruitment will greatly benefit these species in the long term, and other species in the short term.

Some aspects related to this subject have been discussed as ecosystem components and functions under other sections. Findings from the earliest studies of the impacts of fragmentation of riparian habitats on breeding birds were published for the Southwest (Carothers and Johnson 1971, Johnson 1971, Carothers et al. 1974). Subsequent studies by other investigators found similar results. Basically, cottonwood-willow gallery forests of the North American Southwest supported the highest concentrations of noncolonial nesting birds for North America. Destruction and fragmentation of these riparian forests reduced species richness and resulted in a nearly straight-line relationship between numbers of nesting pairs/acre and number of mature trees/acre. Later studies demonstrated that riparian areas are equally important as conduits for migrating birds (Johnson and Simpson 1971, Stevens et al. 1977).

When considering restoration of riparian habitats, the condition of adjacent habitats must be considered. Carothers (1979) found that riparian ecosystems, especially the edges, are widely used by nonriparian birds. In addition he found that some riparian birds utilized adjacent nonriparian ecosystems. Carothers et al. (1974) found that smaller breeding species [e.g., warblers and the Western wood pewee (*Contopus sordidulus*)] tended to carry on all activities within the riparian ecosystem during the breeding season. However, larger species (e.g., kingbirds and doves) commonly foraged outside the riparian ecosystem in adjacent habitats. Larger species (e.g., raptors) may forage miles from riparian ecosystems, but still depend on them in critical ways (Lee et al. 1989).

Because of more mesic conditions created by the canyon effect, canyons and their attendant riparian vegetation serve as corridors for short-range movements of animals along elevational gradients (e.g., between summer and winter ranges). Long-range movements that occur along riparian zones throughout North America include migration of birds and bats. Riparian zones also serve as stopover habitat for migrating birds (Stevens et al. 1977). Woody vegetation is generally important, not only to most riparian ecosystems, but also to adjacent aquatic and even upland ecosystems. However, it is important to establish clear management objectives before attempting habitat modification.

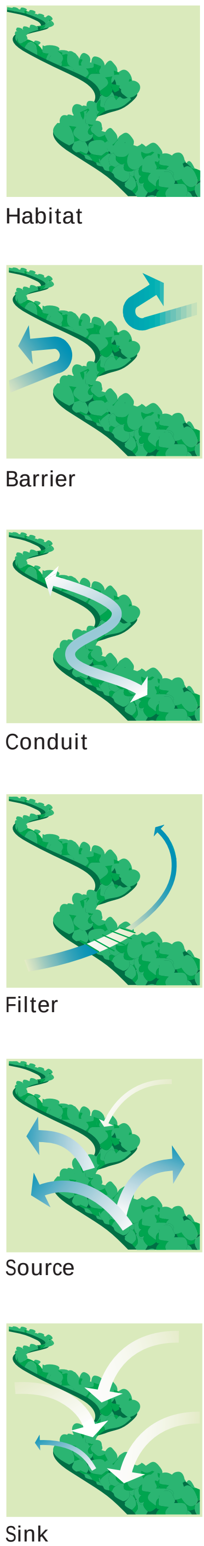
Restoring all of a given ecosystem to its “pristine condition” may be impossible, especially if upstream conditions have been heavily modified, such as by a dam or other water diversion project. Even if complete restoration is a possibility, it may not accomplish or complement the restoration goals.

For example, encroachment of woody vegetation in the channel below several dams in the Platte River Valley in Nebraska has greatly decreased the amount of important wet meadow habitat. This area has been declared critical habitat for the whooping crane

(*Grus americana*) (Aronson and Ellis 1979), for piping plover, and for the interior least tern. It is also an important staging area for up to 500,000 sandhill cranes (*Grus canadensis*) from late February to late April and supports 150 to 250 bald eagles (*Haliaeetus leucocephalus*). Numerous other important species using the area include the peregrine falcon (*Falco peregrinus*), Canada goose (*Branta canadensis*), mallard (*Anas platyrhynchos*), numerous other waterfowl, and raptors (U.S. Fish and Wildlife Service 1981). Thus, managers here are confronted with means of reducing riparian groves in favor of wet meadows.

2.E Functions and Dynamic Equilibrium

Figure 2.37: Critical ecosystem functions.
Six functions can be summarized as a set of basic, common themes recurring in a variety of settings.



Habitat-*the spatial structure of the environment which allows species to live, reproduce, feed, and move.*

Barrier-*the stoppage of materials, energy, and organisms.*

Conduit-*the ability of the system to transport materials, energy, and organisms.*

Filter–*the selective penetration of materials, energy, and organisms.*

Source—*a setting where the output of materials, energy, and organisms exceeds input.*

Sink—*a setting where the input of water, energy, organisms and materials exceeds output.*

Throughout the past two chapters, this document has covered stream corridor structure and the physical, chemical and biological processes occurring in stream corridors. This information shows how stream corridors function as ecosystems, and consequently, how these characteristic structural features and processes must be understood in order to enable stream corridor functions to be effectively restored. In fact, reestablishing structure or restoring a particular physical or biological process is not the only thing that restoration seeks to achieve. Restoration aims to reestablish valued functions. Focusing on ecological functions gives the restoration effort its best chance to recreate a self-sustaining system. This property of sustainability is what separates a functionally sound stream, that freely provides its many benefits to people and the natural environment, from an impaired watercourse that cannot sustain its valued functions and may remain a costly, long-term maintenance burden.

Section 1.A of Chapter 1 emphasized matrix, patch, corridor and mosaic as the most basic building blocks of physical structure at local to regional scales. Ecological functions, too, can be summarized as a set of basic, common themes that recur in an infinite variety of settings. These six critical functions are habitat, conduit, filter, barrier, source, and sink (**Figure 2.37**).

In this section, the processes and structural descriptions of the past two chapters are revisited in terms of these critical ecological functions.

Two attributes are particularly important to the operation of stream corridor functions:

- *Connectivity*- This is a measure of how spatially continuous a corridor or a matrix is (Forman and Godron 1986). This attribute is affected by gaps or breaks in the corridor and between the corridor and adjacent land uses (**Figure 2.38**). A stream corridor with a high degree of connectivity among its natural communities promotes valuable functions including transport of materials and energy and movement of flora and fauna.
- *Width*- In stream corridors, this refers to the distance across the stream and its zone of adjacent vegetation cover. Factors affecting width are edges, community composition, environmental gradients, and disturbance effects of adjacent ecosystems, including those with human activity. Example measures of width include average dimension and variance, number of narrows, and varying habitat requirements (Dramstad et al. 1996)

Width and connectivity interact throughout the length of a stream corridor. Corridor width varies along the length of the stream and may have gaps. Gaps across the corridor interrupt and reduce connectivity. Evaluating connectivity and width can provide some of the most valuable insight for designing restoration actions that mitigate disturbances.

The following subsections discuss each of the functions and general relationship to connectivity and width. The final subsection discusses dynamic equilibrium and its relevance to stream corridor restoration.

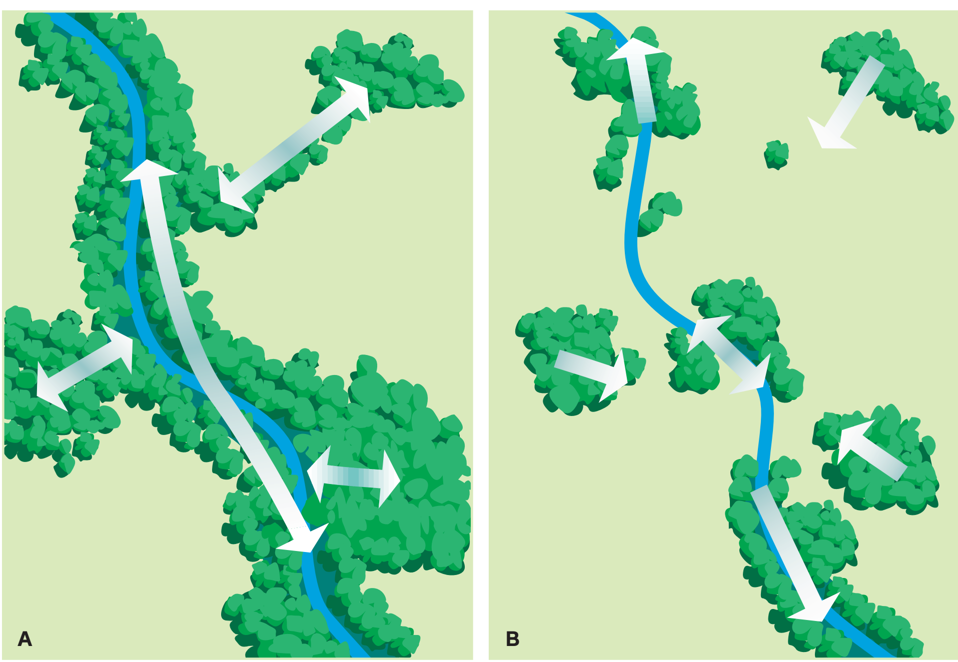
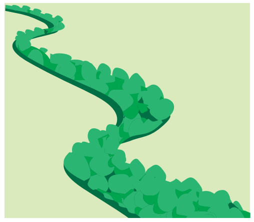


Figure 2.38: Landscapes with *(A)* high and *(B)* low degrees of connectivity.
A connected landscape structure generally has higher levels of functions than a fragmented landscape.

Habitat Functions



Habitat is a term used to describe an area where plants or animals (including people) normally live, grow, feed, reproduce, and otherwise exist for any portion of their life cycle. Habitats provide organisms or communities of organisms with the necessary elements of life, such as space, food, water, and shelter.

Under suitable conditions often provided by stream corridors, many species can use the corridor to live, find food and water, reproduce, and establish viable populations. Some measures of a stable biological community are population size, number of species, and genetic variation, which fluctuate within expected limits over time. To varying degrees, stream corridors constructively influence these measures. The corridor's value as habitat is increased by the fact that corridors often connect many small habitat patches and thereby create larger, more complex habitats with larger wildlife populations and higher biodiversity.

Habitat functions differ at various scales, and an appreciation of the scales at which different habitat functions occur will help a restoration initiative succeed. The evaluation of habitat at larger scales, for example, may make note of a biotic community's size, composition, connectivity and shape.

At the landscape scale, the concepts of matrix, patches, mosaics and corridors are often involved in describing habitat over large areas. Stream corridors and major river valleys together can provide substantial habitat. North American flyways include examples of stream and river corridor habitat exploited by migratory birds at landscape to regional scales.

Stream corridors, and other types of naturally vegetated corridors as well, can provide migrating forest and riparian species with their preferred resting and feeding habitats during migration stopovers. Large mammals such as black bear are known to require large, contiguous wild terrain as home range, and in many parts of the country broad stream corridors are crucial to linking smaller patches into sufficiently large territories.

Habitat functions within watersheds may be examined from a somewhat different perspective. Habitat types and patterns within the watershed are significant, as are patterns of connectivity to adjoining watersheds. The vegetation of the stream corridor in upper reaches of watersheds sometimes has become disconnected from that of adjacent watersheds and corridors beyond the divide. When terrestrial or semiaquatic stream corridor communities are connected at their headwaters, these connections will usually help provide suitable alternative habitats beyond the watershed.

Assessing habitat function at the stream corridor and smaller scales can also be viewed in terms of patches and corridors, but in finer detail than in landscapes and watersheds. It is also at local scales that transitions among the

Edge and Interior Habitat

Two important habitat characteristics are edges and interior (**Figure 2.39**) Edges are critical lines of interaction between different ecosystems. Interior habitats are generally more stable, sheltered environments where the ecosystem may remain relatively the same for prolonged periods. Edge habitat is exposed to highly variable environmental gradients. The result is a different species composition and abundance than observed interior habitat. Edges are important as filters of disturbance to interior habitat. Edges can also be diverse areas with a large variety of flora and fauna.

Edges and interiors are scale-independent concepts. Larger mammals known as interior forest species may need to be miles from the forest edge to find desired habitat, while an insect or amphibian may be sensitive to the edges and interiors of the microhabitat under a rotted log. The edges and interiors of a stream corridor, therefore, depend upon the species being considered. As elongated, narrow ecosystems that include land/water interfaces and often include natural/human-made boundaries as well at the upland fringe, stream corridors have an abundance of edges and these have a pronounced effect on their biota.

Edges and interiors are each preferred by different sets of plant and animal species, and it is inappropriate to consider edges or interiors as consistently “bad” or “good” habitat characteristics. It may be desirable to maintain or increase edge in some circumstances, or favor interior habitats in others. Generally speaking, however, human activity tends to increase edge and decrease interior, so more often it is restoring or protecting interior that merits specific management action.

Edge habitat at the stream corridor boundary typically has higher inputs of solar energy, precipitation, wind energy, and other influences from the adjacent ecosystems. The difference in environmental gradients at the stream corridor’s edge results in a diversified plant and animal community interacting with adjacent ecosystems. The effect of edge is more pronounced when the amount of interior habitat is minimal.

Interior habitat occurs further from the perimeter of the element. Interior is typified by more stable environmental inputs than those found at the edge of an ecosystem. Sunlight, rainfall, and wind effects are less intense in the interior. Many sensitive or rare species depend upon a less-disturbed environment for their survival. They are therefore tolerant of only “interior” habitat conditions. The distance from the perimeter required to create these interior conditions is dependent upon the species’ requirements.

Interior plants and animals differ considerably from those that prefer or tolerate the edge’s variability. With an abundance of edge, stream corridors often have mostly edge species. Because large ecosystems and wide corridors are becoming increasingly fragmented in modern landscapes, however, interior species are often rare and hence are targets for restoration. The habitat requirements of interior species (with respect to distance from edge are a useful guide in restoring larger stream corridors to provide a diversity of habitat types and sustainable communities.

Figure 2.39: Edge and interior habitat of a woodlot

Interior plants and animals differ considerably from those that prefer or tolerate the edge’s variability.

various habitats within the corridor can become more important. Stream corridors often include two general types of habitat structure: interior and edge habitat. Habitat diversity is increased by a corridor that includes both edge and interior conditions, although for most streams, corridor width is insufficient to provide much interior habitat for larger vertebrates such as forest interior bird species. For this reason, increasing interior habitat is sometimes a watershed scale restoration objective.

Habitat functions at the corridor scale are strongly influenced by connectivity and width. Greater connectivity and increased width along and across a stream corridor generally increases its value as habitat. Stream valley morphology and environmental gradients (such as gradual changes in soil wetness, solar radiation, and precipitation) can cause changes in plant and animal communities. More species generally find suitable habitat conditions in a wide, contiguous, and diverse assortment of native plant communities within the stream corridor than in a narrow, homogeneous or highly fragmented corridor.

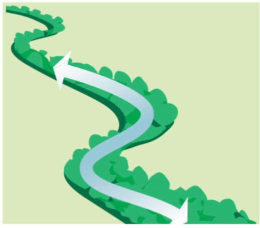
When applied strictly to stream channels, however, this might not be true. Some narrow and deeply incised streams, for example, provide thermal conditions that are critical for endangered salmonids.

Habitat conditions within a corridor vary according to factors such as climate and microclimate, elevation, topography, soils, hydrology, vegetation, and human uses. In terms of planning restoration measures, corridor width is especially important for wildlife. When planning for maintenance of a given wildlife species, for example, the dimension and shape of the corridor must be wide enough to include enough suitable habitat that this species can populate the stream corridor. Corridors that are too narrow may provide as much of a barrier to some species' movement as would a complete gap in the corridor.

On local scales, large woody debris that becomes lodged in the stream channel can create morphological changes to the stream and adjacent streambanks. Pools may be formed downstream from a log that has fallen across a stream and both upstream and downstream flow characteristics are altered. The structure formed by large woody debris in a stream improves aquatic habitat for most fish and invertebrate species.

Riparian forests, in addition to their edge and interior habitats, may offer vertical habitat diversity in their canopy, subcanopy, shrub and herb layers. And within the channel itself, riffles, pools, glides, rapids and backwaters all provide different habitat conditions in both the water column and the streambed. These examples, all described in terms of physical structure, illustrate once again the strong linkage between structure and habitat function.

Conduit Function



The conduit function is the ability to serve as a flow pathway for energy, materials, and organisms. A stream corridor is above all a conduit that was formed by and for collecting and transporting water and sediment. In addition, many other types of materials and biota move throughout the system.

The stream corridor can function as a conduit laterally, as well as longitudinally, with movement by organisms and materials in any number of directions. Materials or animals may further move across the stream corridor, from one side to another. Birds or small mammals, for example, may cross a stream with a closed canopy by moving through its vegetation. Organic debris and nutrients may fall from higher to lower floodplains and into the stream within corridors, affecting the food supply for stream invertebrates and fishes.

Moving material is important because it impacts the hydrology, habitat, and structure of the stream as well as the terrestrial habitat and connections in the floodplain and uplands. The structural attributes of connectivity and width also influence the conduit function.

For migratory or highly mobile wildlife, corridors serve as habitat and conduit simultaneously. Corridors in combination with other suitable habitats, for example, make it possible for songbirds to move from wintering habitat in the neo-tropics to northern, summer habitats. Many species of birds can only fly for limited distances before they must rest and refuel. For stream corridors to function effectively as conduits for these birds, they must be sufficiently connected and be wide enough to provide required migratory habitat.

Stream corridors are also conduits for the movement of energy, which occurs in many forms. The gravity-driven energy of stream flow continually sculpts and modifies the landscape. The corridor modifies heat and energy from sunlight as it remains cooler in spring and summer and warmer in the fall. Stream valleys are effective airsheds, moving cool air from higher to lower elevations in the evening. The highly productive plant communities of a corridor accumulate energy as living plant material, and export large amounts in the form of leaf fall or detritus. The high levels of primary productivity, nutrient flow, and leaf litter fall also fuel increased decomposition in the corridor, allowing new transformations of energy and materials. At its outlet, a stream's outputs to the next larger water body (e.g., increased water volume, higher temperature, sediments, nutrients, and organisms) are in part the excesses of energy from its own system.

One of the best known and studied examples of aquatic species movement and interaction with the watershed is the migration of salmon upstream for spawning. After maturing in the ocean, the fish are dependent on access to their upstream spawning grounds. In the case of Pacific salmon species, the stream corridor is dependent upon the resultant biomass and nutrient input of abundant spawning and dying adults into the upper reaches of stream systems during spawning. Thus, connectivity is often critical for aquatic species transport, and in turn, nutrient transport upstream from ocean waters to stream headwaters.

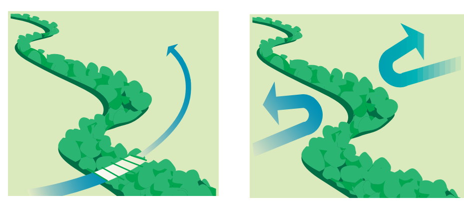
Streams are also conduits for distribution of plants and their establishment in new areas (Malanson, 1993). Flowing water may transport and deposit seeds over considerable distances. In flood stage, mature plants may be uprooted, relocated, and redeposited alive in new locations. Wildlife also help redistribute plants by ingesting and transporting seeds throughout different parts of the corridor.

Sediment (bed load or suspended load) is also transported through the stream. Alluvial streams are dependent on the continual supply and transport of sediment, but many of their fish and invertebrates can also be harmed by too much fine sediment. When conditions are altered, a stream may become either starved of sediment or choked with sediment down-gradient. Streams lacking appropriate amounts of sediment attempt to reestablish equilibrium through downcutting, bank erosion and channel erosion. An appropriately structured stream corridor will optimize timing and supply of sediment to the stream to improve sediment transport functions.

Local areas in the corridor are dependent on the flow of materials from one point to another. In the salmonid example, the local upland area adjacent to spawning grounds is dependent upon the nutrient transfer from the biomass of the fish into other terrestrial wildlife and off into the uplands. The local structure of the streambed and aquatic ecosystem are dependent upon the sediment and woody material from upstream and upslope to create a self-regulating and stable channel.

Stream corridor width is important where the upland is frequently a supplier of much of the natural load of sediment and biomass into the stream. A wide, contiguous corridor acts as a large conduit, allowing flow laterally and longitudinally along the corridor. Conduit functions are often more limited in narrow or fragmented corridors.

Filter and Barrier Functions



Stream corridors may serve as barriers that prevent movement or filters that allow selective penetration of energy, materials and organisms. In many ways, the entire stream corridor serves beneficially as a filter or barrier that reduces water pollution, minimizes sediment transport, and often provides a natural boundary to land uses, plant communities, and some less mobile wildlife species.

Materials, energy, and organisms which moved into and through the stream corridor may be filtered by structural attributes of the corridor. Attributes affecting barrier and filter functions include connectivity (gap

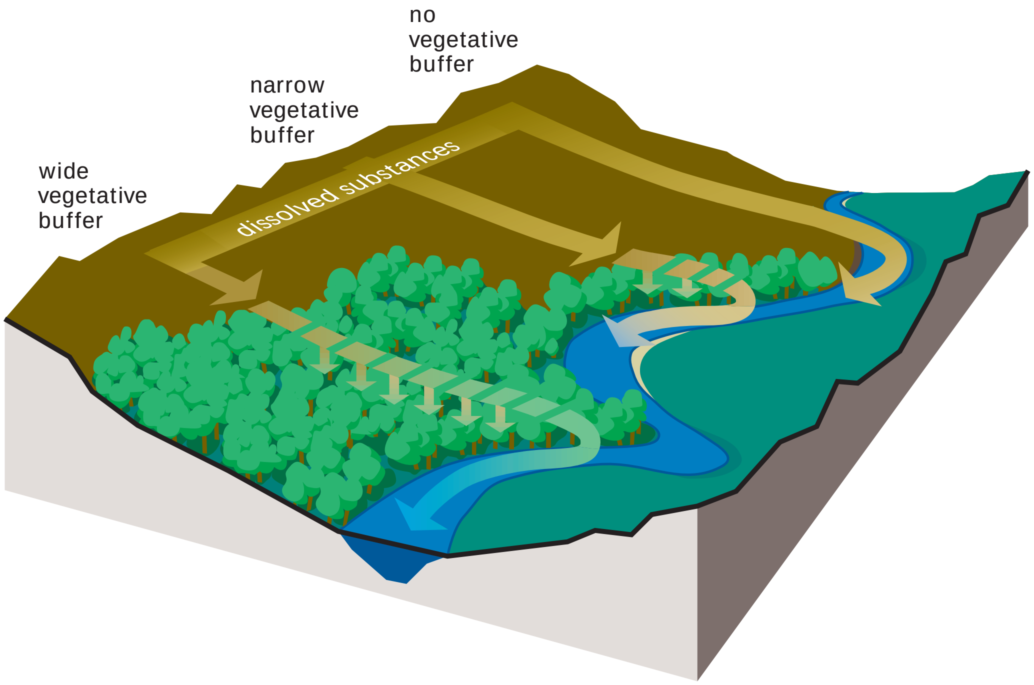


Figure 2.40: The width of the vegetation buffer influences filter and barrier functions *Dissolved substances, such as nitrogen, phosphorus, and other nutrients, entering a vegetated stream corridor are restricted from entering the channel by friction, root absorption, clay, and soil organic matter.* **Adapted from *Ecology of Greenways: Design and Function of Linear Conservation Areas*. Edited by Smith and Hellmund. © University of Minnesota Press 1993.**

frequency), and corridor width (**Figure 2.40**). Elements which are moving along a stream corridor edge may also be selectively filtered as they enter the stream corridor. In these circumstances it is the shape of the edge, whether it is straight or convoluted, which has the greatest effect on filtering functions. Still, it is most often movement perpendicular to the stream corridor which is most effectively filtered or halted.

Materials may be transported, filtered, or stopped altogether depending upon the width and connectedness of a stream corridor. Material movement across landscapes toward large river valleys may be intercepted and filtered by stream corridors. Attributes such as the structure of native plant communities can physically affect the amount of runoff entering a stream system through uptake, absorption, and interruption. Vegetation in the corridor can filter out much of the overland flow of nutrients, sediment, and water.

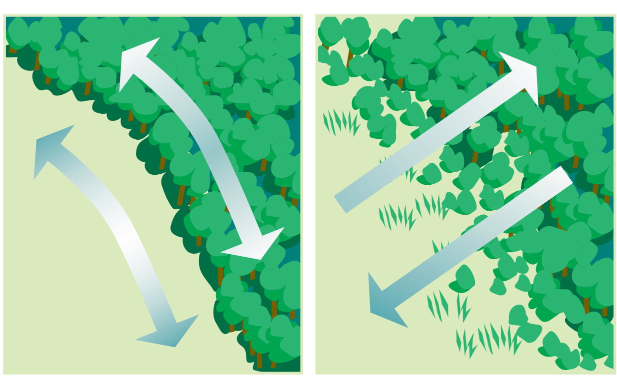
Siltation in larger streams can be reduced through a network of stream corridors functioning to filter excessive sediment. Stream corridors filter many of the upland materials from moving unimpeded across the landscape. Ground water and surface water flows are filtered by plant parts below and above ground. Chemical elements are intercepted by flora and fauna within stream corridors. A wider corridor provides more effective filtering, and a contiguous corridor functions as a filter along its entire length.

Breaks in a stream corridor can sometimes have the effect of funneling damaging processes into that area. For example, a gap in contiguous vegetation along a stream corridor can reduce the filtering function by focusing increased runoff into the area, leading to erosion, gullying, and the free flow of sediments and nutrients into the stream.

Edges at the boundaries of stream corridors begin the process of filtering. Abrupt edges concentrate initial filtering functions into a narrow area. A gradual edge increases filtering and spreads it across a wider ecological gradient. (**Figure 2.41**).

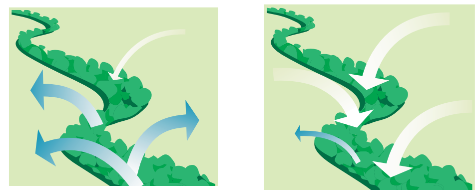
Movement parallel to the corridor is affected by coves and lobes of an uneven corridor's edge. These act as barriers or filters for materials flowing into the corridor. Individual plants may selectively capture materials such as wind-borne sediment, carbon, or propagules as they pass through a convoluted edge. Herbivores traveling along a boundary edge, for example, may stop to rest and selectively feed in a sheltered nook. The wind blows a few seeds into the corridor, and those suited to the conditions of the corridor may germinate and establish a population. The lobes have acted as a selective filter collecting some seeds at the edge and allowing other species to interact at the boundary (Forman 1995).

Figure 2.39: Edges can be (a) abrupt or (b) gradual.
Abrupt edges, usually caused by disturbances, tend to discourage movement between ecosystems and promote movement along the boundary. Gradual edges usually occur in natural settings, are more diverse, and encourage movement between ecosystems.



(a) *(b)*

Source and Sink Functions



Sources provide organisms, energy or materials to the surrounding landscape. Areas that function as sinks absorb organisms, energy, or materials from the surrounding landscape. Influent and effluent reaches, discussed in Section 1.B of Chapter 1, are classic examples of sources and sinks. The influent or "losing" reach is a source of water to the aquifer, and the effluent or "gaining" reach is a sink for ground water.

Stream corridors or features within them can act as a source or a sink of environmental materials. Some stream corridors act as both, depending on the time of year or location in the corridor. Streambanks most often act as a source, for example, of sediment to the stream. At times, however, they can function as sinks while flooding deposits new sediments there. At the landscape scale, corridors are connectors to various other patches of habitats in the landscape and as such they are sources and conduits of genetic material throughout the landscape.

Stream corridors can also act as a sink for storage of surface water, ground water, nutrients, energy, and sediment allowing for materials to be temporarily fixed in the corridor. Dissolved substances, such as nitrogen, phosphorus, and other nutrients, entering a vegetated stream corridor are restricted from entering the channel by friction, root absorption, clay, and soil organic matter. Although these functions of source and sink are conceptually understood, they lack a suitable body of research and practical application guidelines.

Forman (1995) offers three source and sink functions resulting from floodplain vegetation:

- Decreased downstream flooding through floodwater moderation and/or uptake
- Containment of sediments and other materials during flood stage
- Source of soil and water organic matter

Biotic and genetic source/sink relationships can be complex. Interior forest birds are vulnerable to nest parasitism by cowbirds when they try to nest in too small a forest patch. For these species, small forest patches can be considered sinks that reduce their population numbers and genetic diversity by causing failed reproduction. Large forest patches with sufficient interior habitat, in comparison, support successful reproduction and serve as sources of more individuals and new genetic combinations.

Dynamic Equilibrium

The first two chapters of this document have emphasized that, although stream corridors display consistent patterns in their structure, processes, and functions, these patterns change naturally and constantly, even in the absence of human disturbance. Despite frequent change, streams and their corridors exhibit a dynamic form of stability. In constantly changing ecosystems like stream corridors, stability is the ability of a system to persist within a range of conditions. This phenomenon is referred to as *dynamic equilibrium*.

The maintenance of dynamic equilibrium requires that a series of self-correcting mechanisms be active in the stream corridor ecosystem. These mechanisms allow the ecosystem to control external stresses or disturbances within a certain range of responses thereby maintaining a self-sustaining condition. The threshold levels associated with these ranges are difficult to identify and quantify. If they are exceeded, the system can become unstable. Corridors may then undergo a series of adjustments to achieve a new steady state condition, but usually after a long period of time has elapsed.

Many stream systems can accommodate fairly significant disturbances and still return to functional condition in a reasonable time frame, once the source of the disturbance is controlled or removed. Passive restoration is based on this tendency of ecosystems to heal themselves when external stresses are removed. Often the removal of stress and the time to recover naturally are an economical and effective restoration strategy. When significant disturbance and alteration has occurred, however, a stream corridor may require several decades to restore itself. Even then, the recovered system may be a very different type of stream that, although at equilibrium again, is of severely diminished ecological value in comparison with its previous potential. When restoration practitioners' analysis indicates lengthy recov-

In constantly changing ecosystems like stream corridors, stability is the ability of a system to persist within a range of conditions. This phenomenon is referred to as *dynamic equilibrium*.

Stability, Disturbance, and Recovery

Stability, as a characteristic of ecosystems, combines the concepts of resistance, resilience, and recovery. *Resistance* is the ability to maintain original form and functions. *Resilience* is the rate at which a system returns to a stable condition after a disturbance. *Recovery* is the degree to which a system returns to its original condition after a disturbance. Natural systems have developed ways of coping with disturbance, in order to produce recovery and stability. Human activities often superimpose additional disturbances which may exceed the recovery capability of a natural system. The fact that change occurs, however, does not always mean a system is unstable or in poor condition.

The term mosaic stability is used to denote the stability of a larger system within which local changes still take place. Mosaic stability, or the lack thereof, illustrates the importance of the landscape perspective in making site-specific decisions. For example, in a rapidly urbanizing landscape, a riparian system denuded by a 100-year flood may represent a harmful break in already diminished habitat that splits and isolates populations of a rare amphibian species. In contrast, the same riparian system undergoing flooding in a less-developed landscape may not be a geographic barrier to the amphibian, but merely the mosaic of constantly shifting suitable and unsuitable habitats in an unconfined, naturally functioning stream. The latter landscape with mosaic stability is not likely to need restoration while the former landscape without mosaic stability is likely to need it urgently. Successful restoration of any stream corridor requires an understanding of these key underlying concepts.

ery time or dubious recovery potential for a stream, they may decide to use active restoration techniques to reestablish a more functional channel form, corridor structure, and biological community in a much shorter time frame. The main benefit of an active restoration approach is regaining functionality more quickly, but the biggest challenge is to plan, design and implement correctly to reestablish the desired state of dynamic equilibrium.

This new equilibrium condition, however, may not be the same that existed prior to the initial occurrence of the disturbance. In addition, disturbances can often stress the system beyond its natural ability to recover. In these instances restoration is needed to remove the cause of the disturbance or stress (passive) or to repair damages to the structure and functions of the stream corridor ecosystem (active).